LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

Hard Probes 2016
Student Lectures
September 2016

Jets
Jet algorithms and jet substructure

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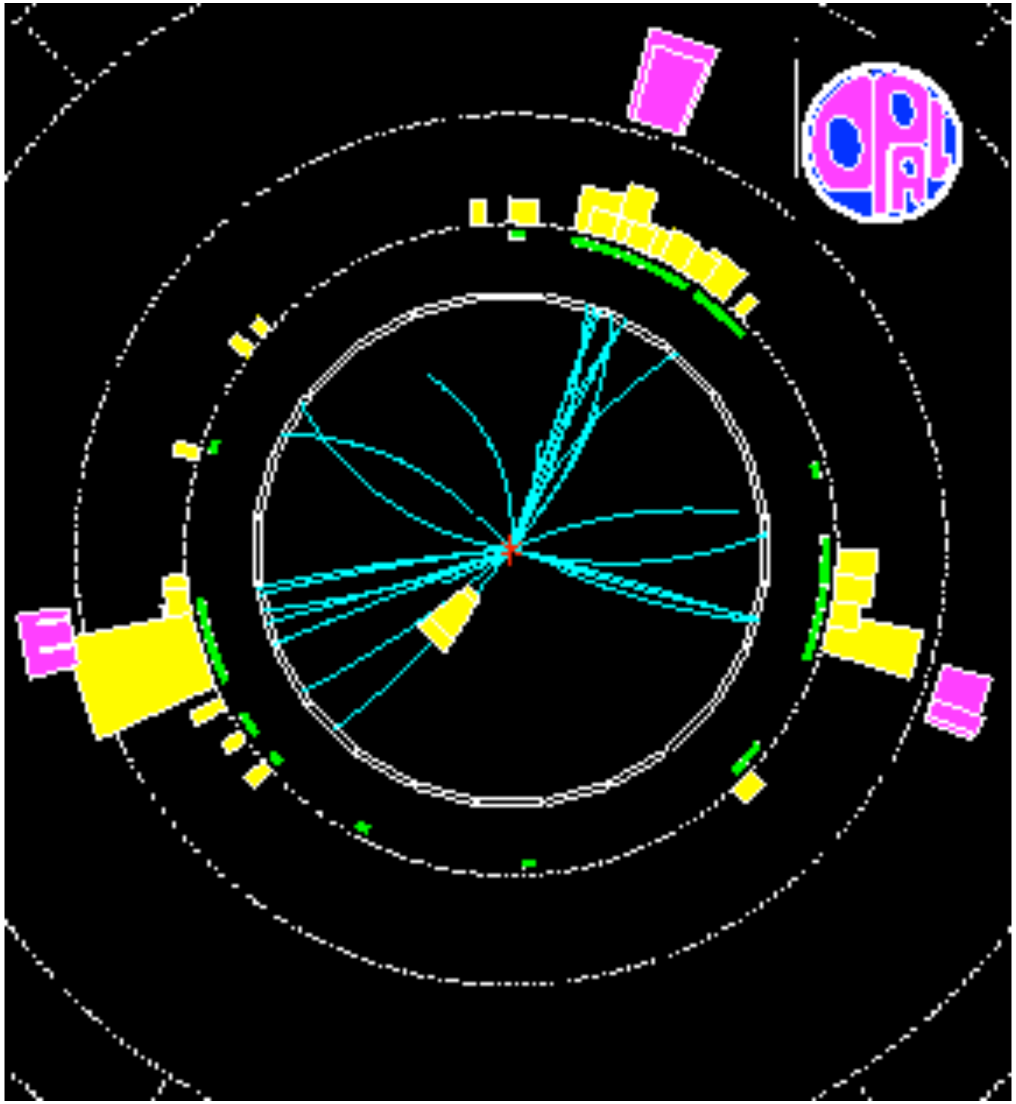
Includes material from
Gavin Salam and Grégory Soyez

Outline

- Jet algorithms
  - How jets are made
- Background
  - How to "clean them up"
- Jet substructure
  - What's inside them

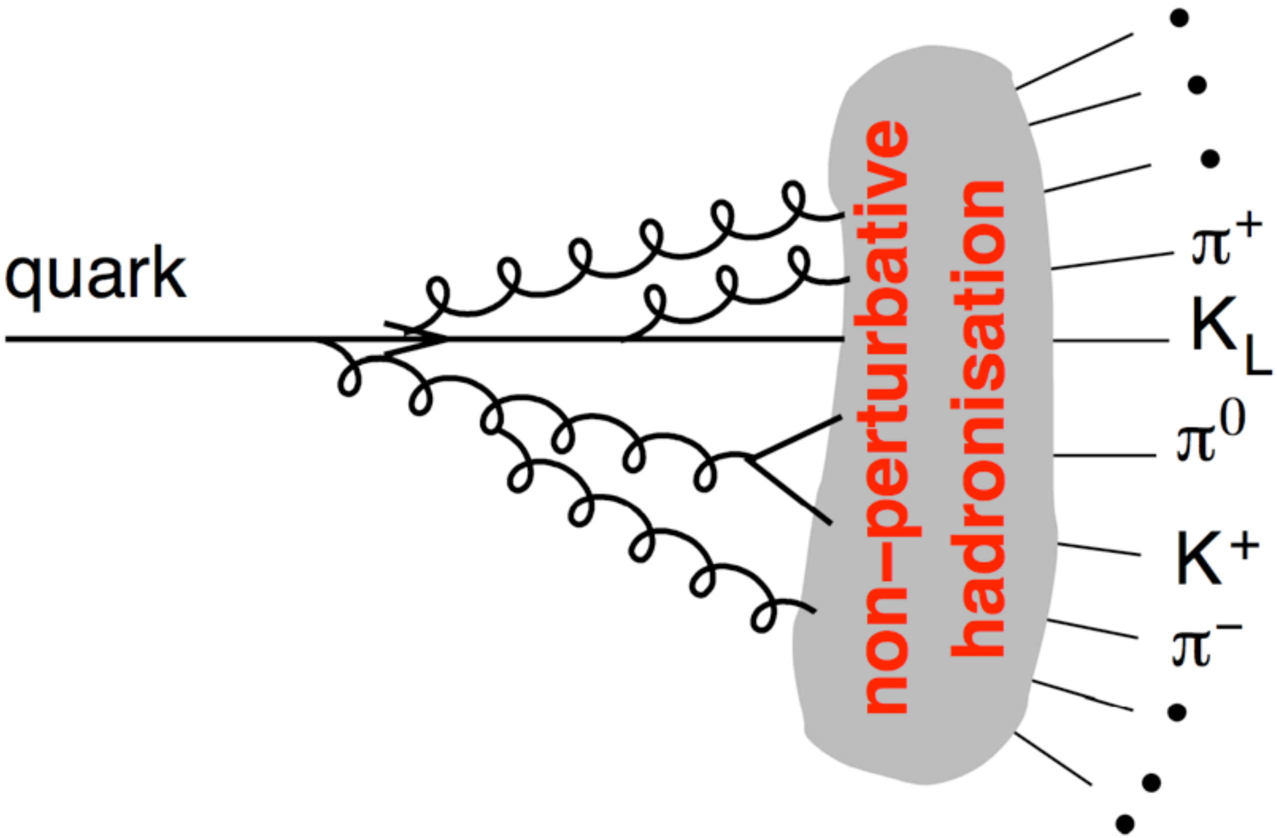


A **jet** is something that happens in high energy events: **a collimated bunch of hadrons flying roughly in the same direction**

We could eyeball the collimated bunches, but it becomes impractical with millions of events

The classification of particles into jets is best done using a **clustering algorithm**

Why do jets happen?



Gluon emission

$$\int \alpha_s \frac{dE}{E}\frac{d\theta}{\theta} \gg 1$$

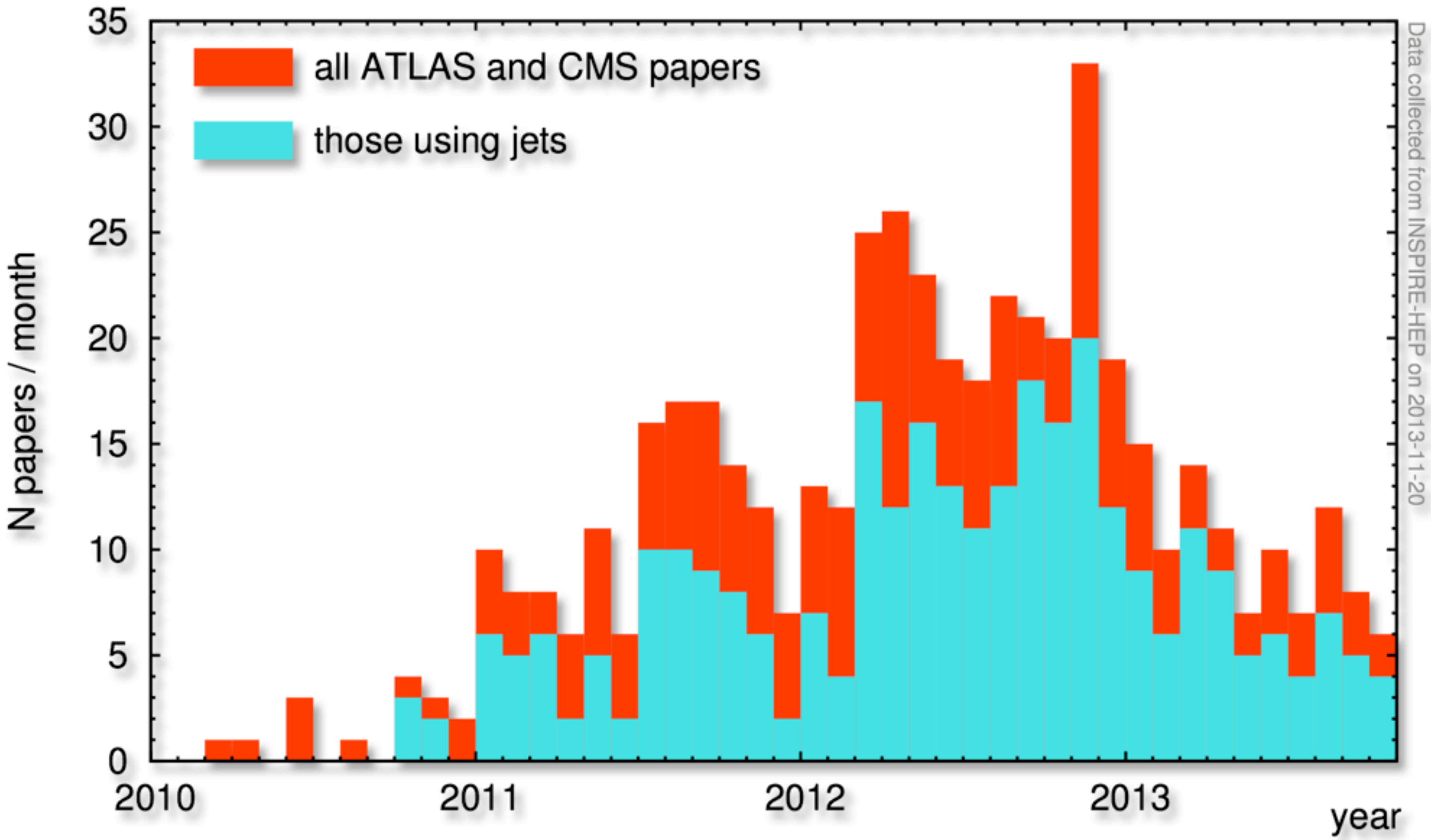
Non-perturbative physics

$$\alpha_s \sim 1$$

Where are jets used?

- ATLAS and CMS have each published **400+** papers since 2010
  - More than **half** of these papers make use of **jets**
  - **60%** of the **searches** papers makes use of **jets**

Plot by G. Salam

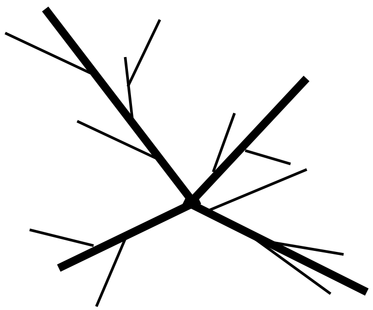


(Source: INSPIRE. Results may vary when employing different search keywords)

Why are jets so important?

Taming reality

Multileg + PS



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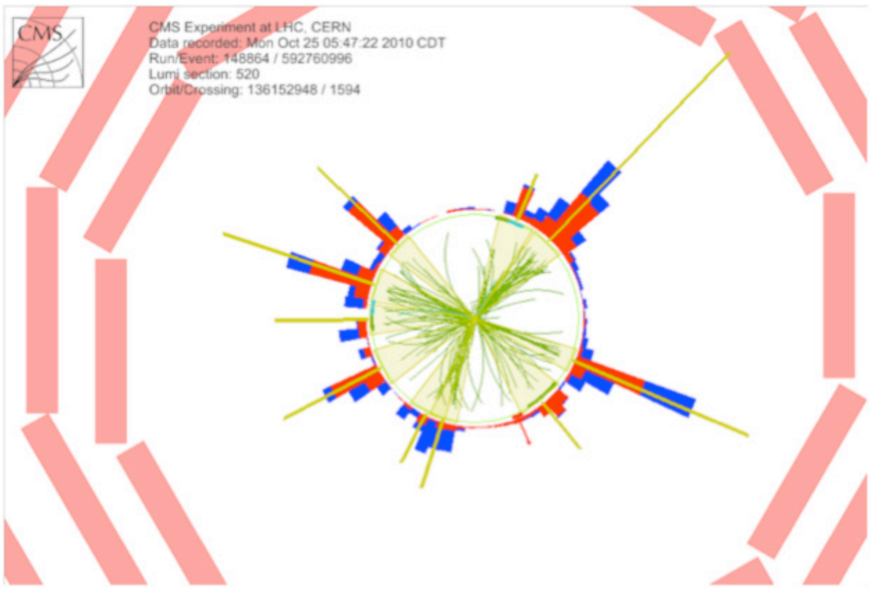


QCD predictions

Real data

Jets

One purpose of a 'jet clustering' algorithm is to **reduce the complexity** of the final state, simplifying many hadrons to **simpler objects** that one can hope to **calculate**

Jets can serve two purposes

- They can be ***observables***, that one can measure and calculate
- They can be ***tools***, that one can employ to extract specific properties of the final state

Different clustering algorithms have different properties and characteristics that can make them more or less appropriate for each of these tasks

Jet clustering algorithm

A **jet algorithm** maps the momenta of the final state particles into the momenta of a certain number of jets:

$$\{p_i\} \xrightarrow{\text{jet algorithm}} \{j_k\}$$

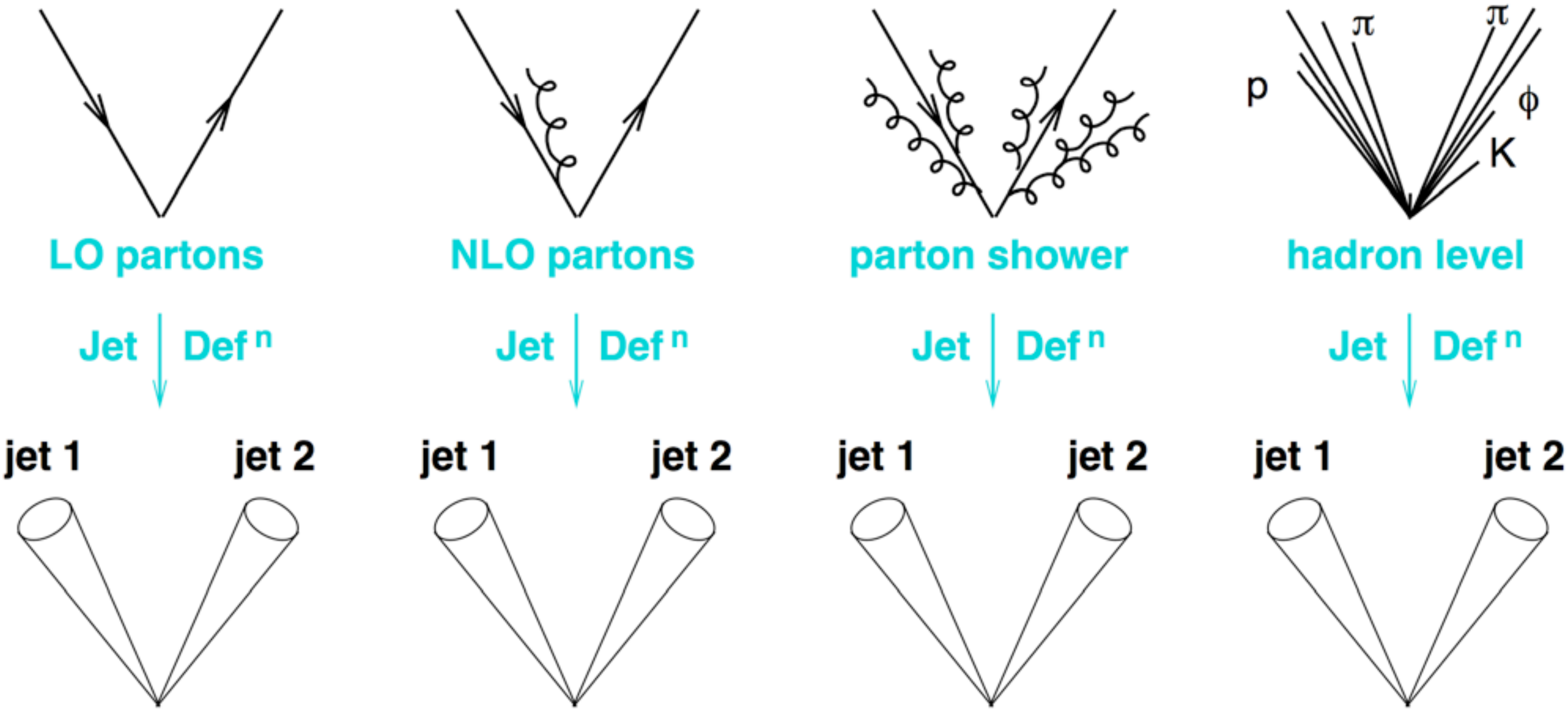
particles,
4-momenta,
calorimeter towers, ...

jets

Most algorithms contain a resolution parameter, **R**, which controls the extension of the jet

Algorithm + parameter(s) + recombination scheme = **jet definition**

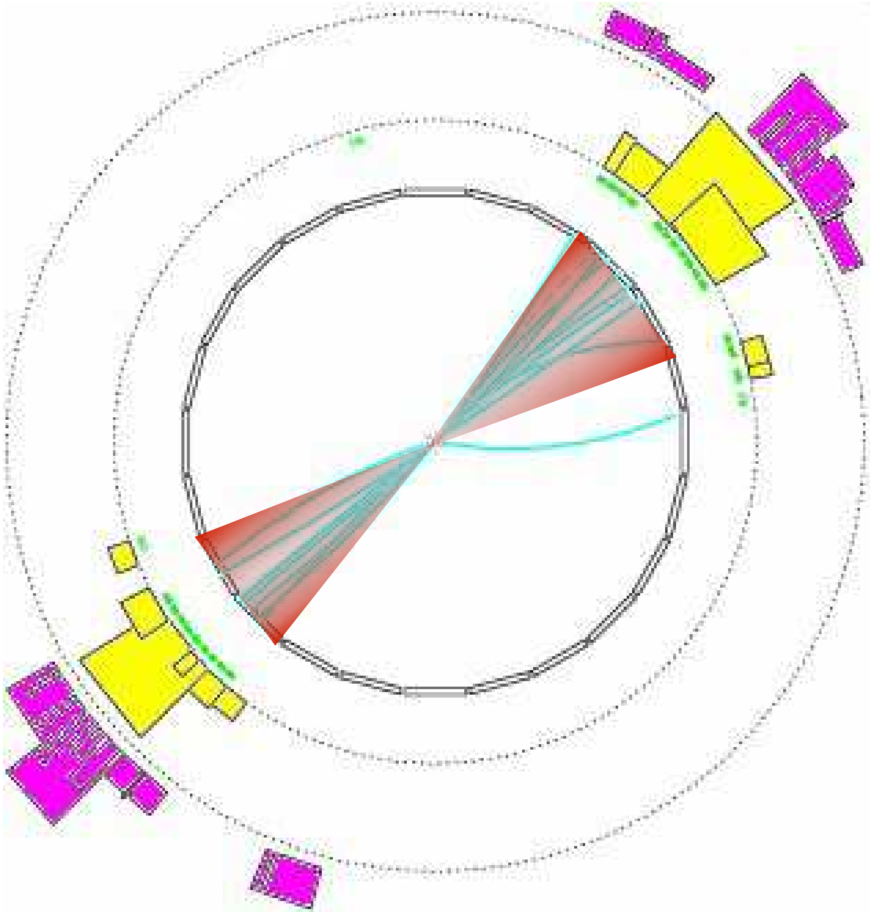
Jet definitions as projections



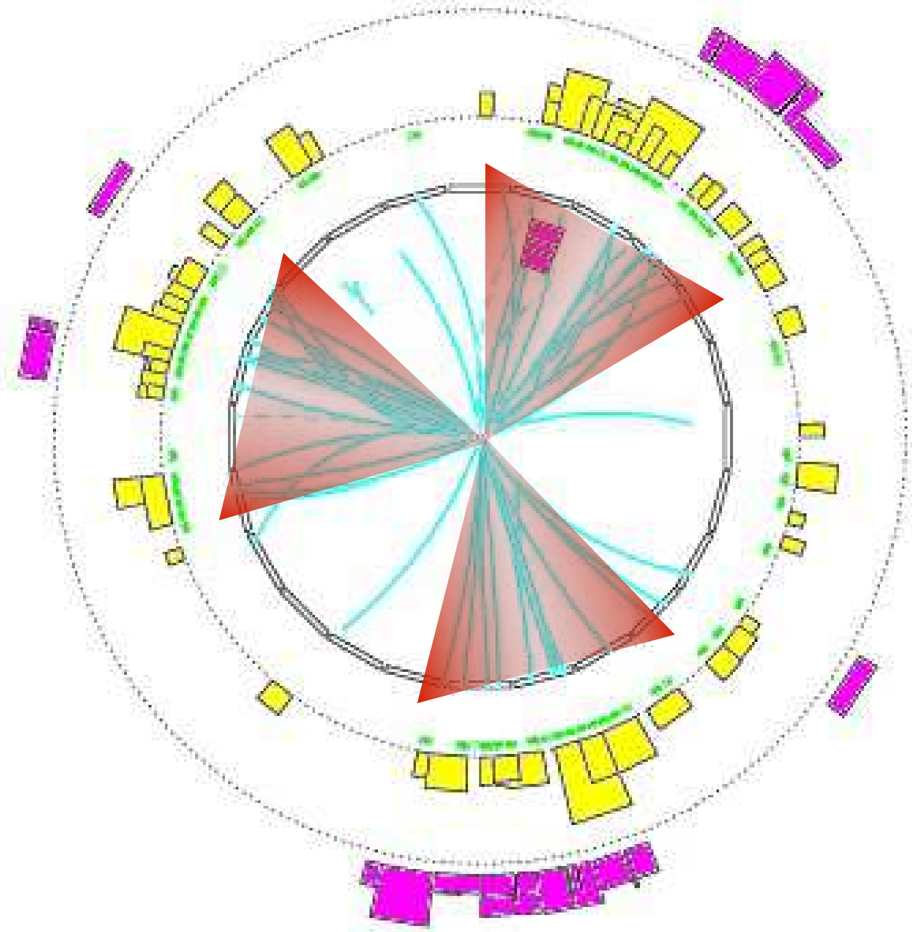
Projection to jets should be resilient to QCD effects

Projections are NOT unique:
a jet is NOT EQUIVALENT to a parton

Reconstructing jets is an ambiguous task

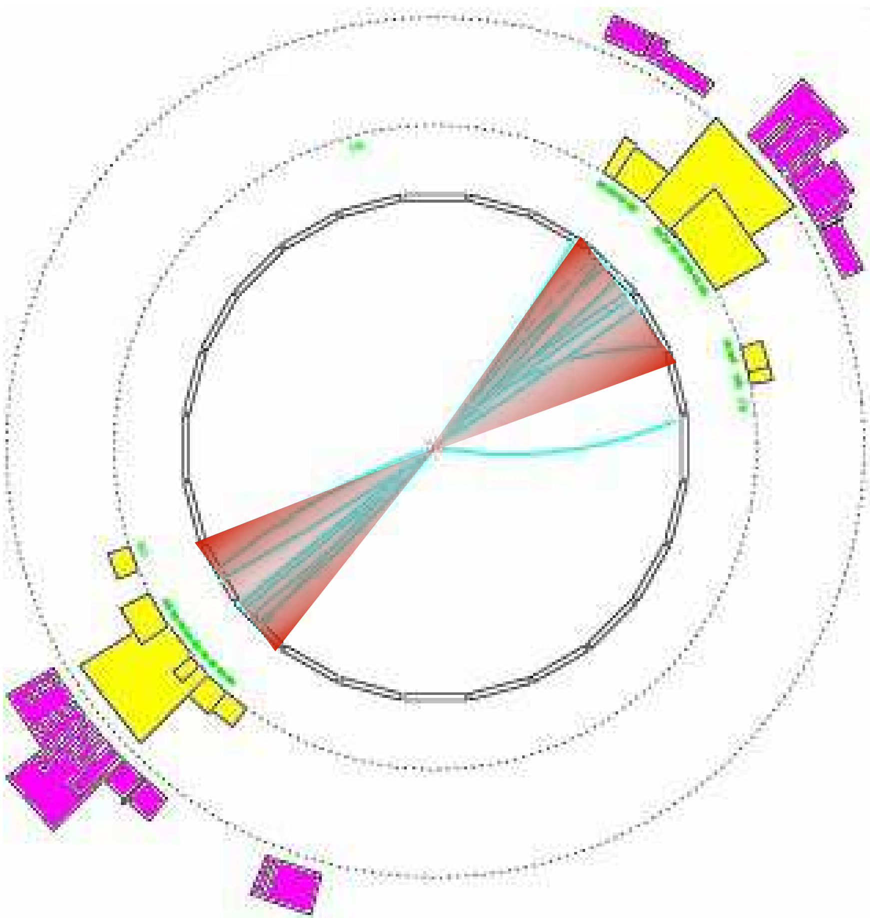


2 clear jets



3 jets?

Reconstructing jets is an ambiguous task



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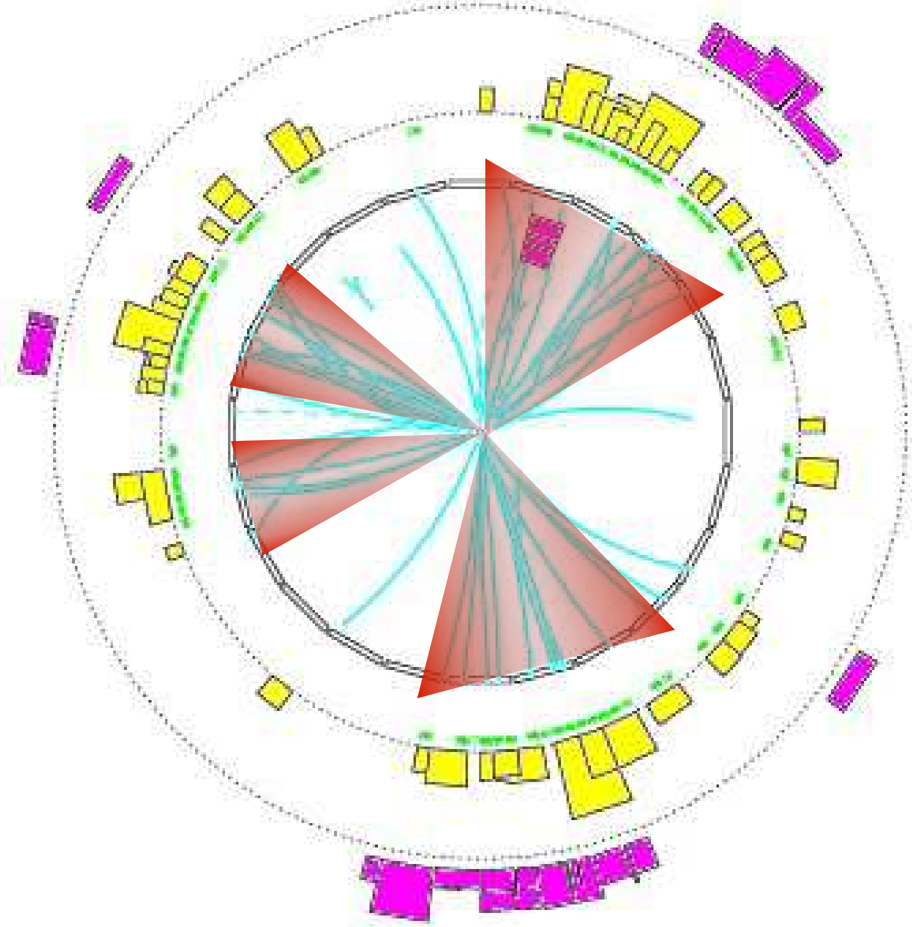
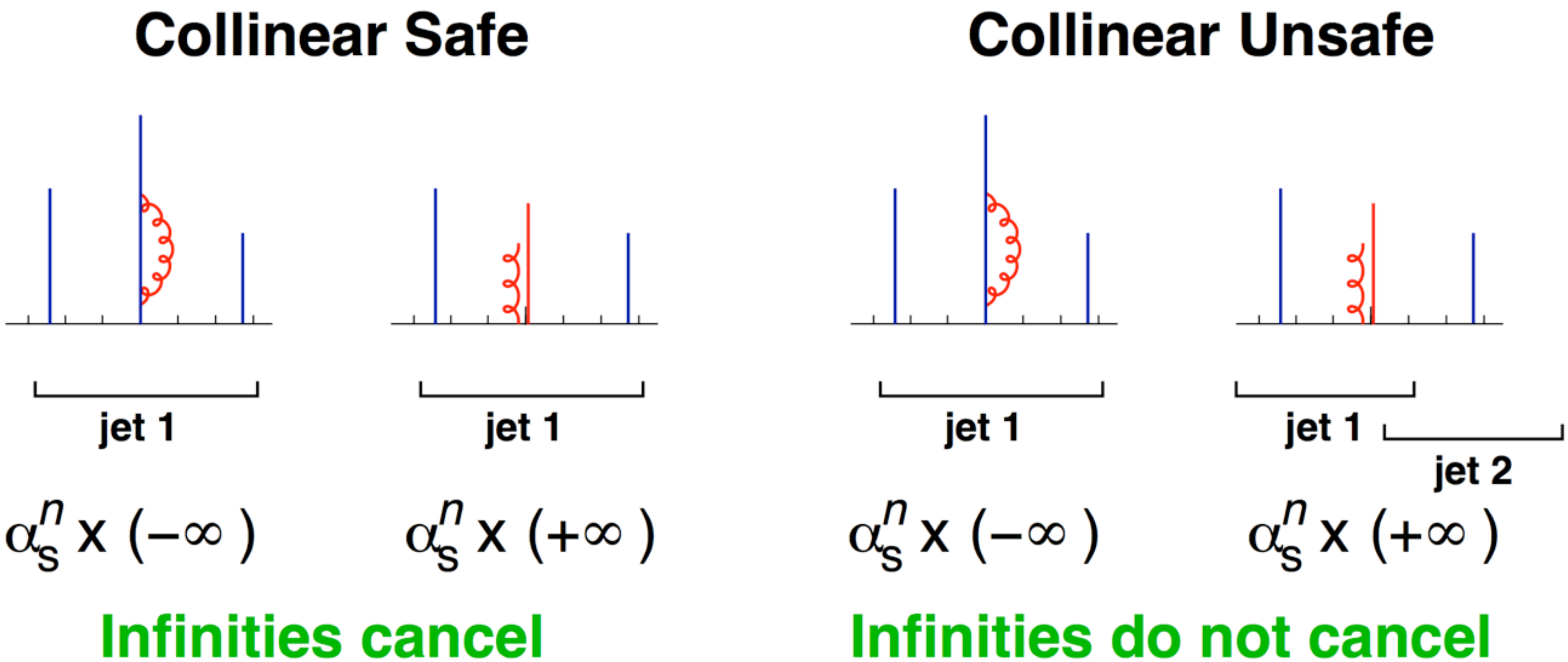


3 jets?
or 4 jets?

Reconstructing jets must respect rules



Perturbative calculations of jet observables
will only be possible with
collinear (and infrared) safe jet definitions

Two main classes of jet algorithms

- **Sequential recombination algorithms (also called hierarchical agglomerative clustering algs.)**

Bottom-up approach: combine particles starting from **closest ones**

How? Choose a **distance measure**, iterate recombination until few objects left, call them jets

Works because of mapping closeness ⇔ QCD divergence

Examples: Jade, k_t, Cambridge/Aachen, anti-k_t, …..

Usually trivially made IRC safe, but their algorithmic complexity scales like N^3.

Modern implementations are fast however.

- **Cone algorithms**

Top-down approach: find coarse regions of energy flow.

How? Find **stable cones** (i.e. their axis coincides with sum of momenta of particles in it)

Works because QCD only modifies energy flow on small scales

Examples: JetClu, MidPoint, ATLAS cone, CMS cone, SISCone…...

Can be programmed to be fairly fast, at the price of being complex and often IRC unsafe (except SISCone)

A little history

- Cone-type jets were introduced first in QCD in the 1970s (Sterman-Weinberg '77)

- In the 1980s cone-type jets were adapted for use in hadron colliders (SppS, Tevatron...) ➙ iterative cone algorithms

- LEP was a golden era for jets: new algorithms and many relevant calculations during the 1990s
  - Introduction of the 'theory-friendly' k_t algorithm
    - sequential recombination type algorithm, IRC safe
    - it allows for all order resummation of jet rates
  - Several accurate calculations in perturbative QCD of jet properties: rates, jet mass, thrust, ...

e^+e^- k_t (Durham) algorithm

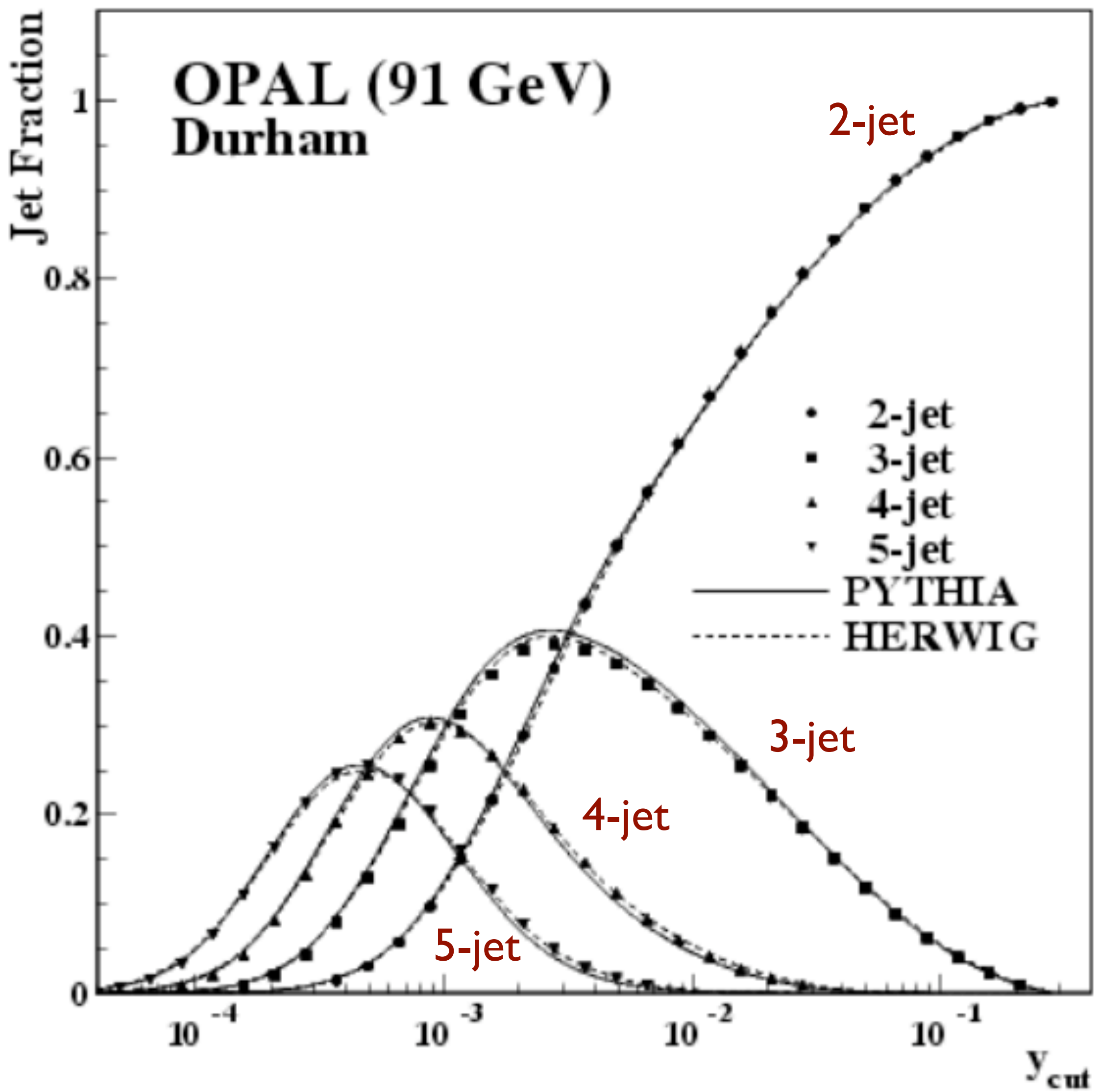
[Catani, Dokshitzer, Olsson, Turnock, Webber '91]

Distance: $$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})}{Q^2}$$

In the collinear limit, the numerator reduces to the **relative transverse momentum** (squared) of the two particles, hence the name of the algorithm

- Find the minimum y_{min} of all y_{ij}
- If y_{min} is below some jet resolution threshold y_{cut}, recombine i and j into a single new particle ('pseudojet'), and repeat
- If no $y_{min} < y_{cut}$ are left, all remaining particles are jets

e^+e^- k_t (Durham) algorithm in action



Characterise events in terms of number of jets (as a function of y_{cut})

Note that the **same** event can be seen to have **different** number of jets according to the value of y_{cut}

Resummed calculations for distributions of y_{cut} doable with the k_t algorithm

e^+e^- k_t (Durham) algorithm v. QCD

k_t is a sequential recombination type algorithm

One key feature of the k_t algorithm is its relation to the structure of QCD divergences:

$$\frac{dP_{k\to ij}}{dE_i d\theta_{ij}} \sim \frac{\alpha_s}{\min(E_i, E_j)\theta_{ij}}$$

The y_{ij} distance is the inverse of the emission probability

- The k_t algorithm roughly inverts the QCD branching sequence (the pair which is recombined first is the one with the largest probability to have branched)

- The history of successive clusterings has physical meaning

Jet challenges at the LHC

The LHC environment differs from the LEP one (and even the Tevatron) under many respects

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- Jets often initiated by a large-momentum heavy particle
  ➙ needs capability to distinguish boosted objet jet from QCD jet

Two parameters, *R* and $p_{t,min}$

(These are the two parameters in essentially every widely used hadron-collider jet algorithm)

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

Sequential recombination algorithm

1. Find smallest of d_{ij}, d_{iB}
2. If *ij*, recombine them
3. If *iB*, call i a jet and remove from list of particles
4. repeat from step 1 until no particles left

Only use jets with $p_t > p_{t,min}$

Inclusive k_t algorithm

S.D. Ellis & Soper, 1993

Catani, Dokshitzer, Seymour & Webber, 1993

The k_t algorithm and its siblings

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

p = 1 k_t algorithm

S. Catani, Y. Dokshitzer, M. Seymour and B. Webber, Nucl. Phys. B406 (1993) 187
S.D. Ellis and D.E. Soper, Phys. Rev. D48 (1993) 3160

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p = -1 anti-k_t algorithm

MC, G. Salam and G. Soyez, arXiv:0802.1189

In anti-kt pairs with a **hard** particle will cluster first: if no other hard particles are close by, the algorithm will give **perfect cones**

Quite ironically, a sequential recombination algorithm is the 'perfect' cone algorithm

IRC safety of generalised-k_t algorithms

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

p > 0

New **soft** particle ($p_t \to 0$) means that d → 0 ⇒ clustered first, no effect on jets

New **collinear** particle ($\Delta y^2 + \Delta\Phi^2 \to 0$) means that d → 0 ⇒ clustered first, no effect on jets

p = 0

New **soft** particle ($p_t \to 0$) can be new jet of zero momentum ⇒ no effect on hard jets

New **collinear** particle ($\Delta y^2 + \Delta\Phi^2 \to 0$) means that d → 0 ⇒ clustered first, no effect on jets

p < 0

New **soft** particle ($p_t \to 0$) means d → ∞ ⇒ clustered last or new zero-jet, no effect on hard jets

New **collinear** particle ($\Delta y^2 + \Delta\Phi^2 \to 0$) means that d → 0 ⇒ clustered first, no effect on jets

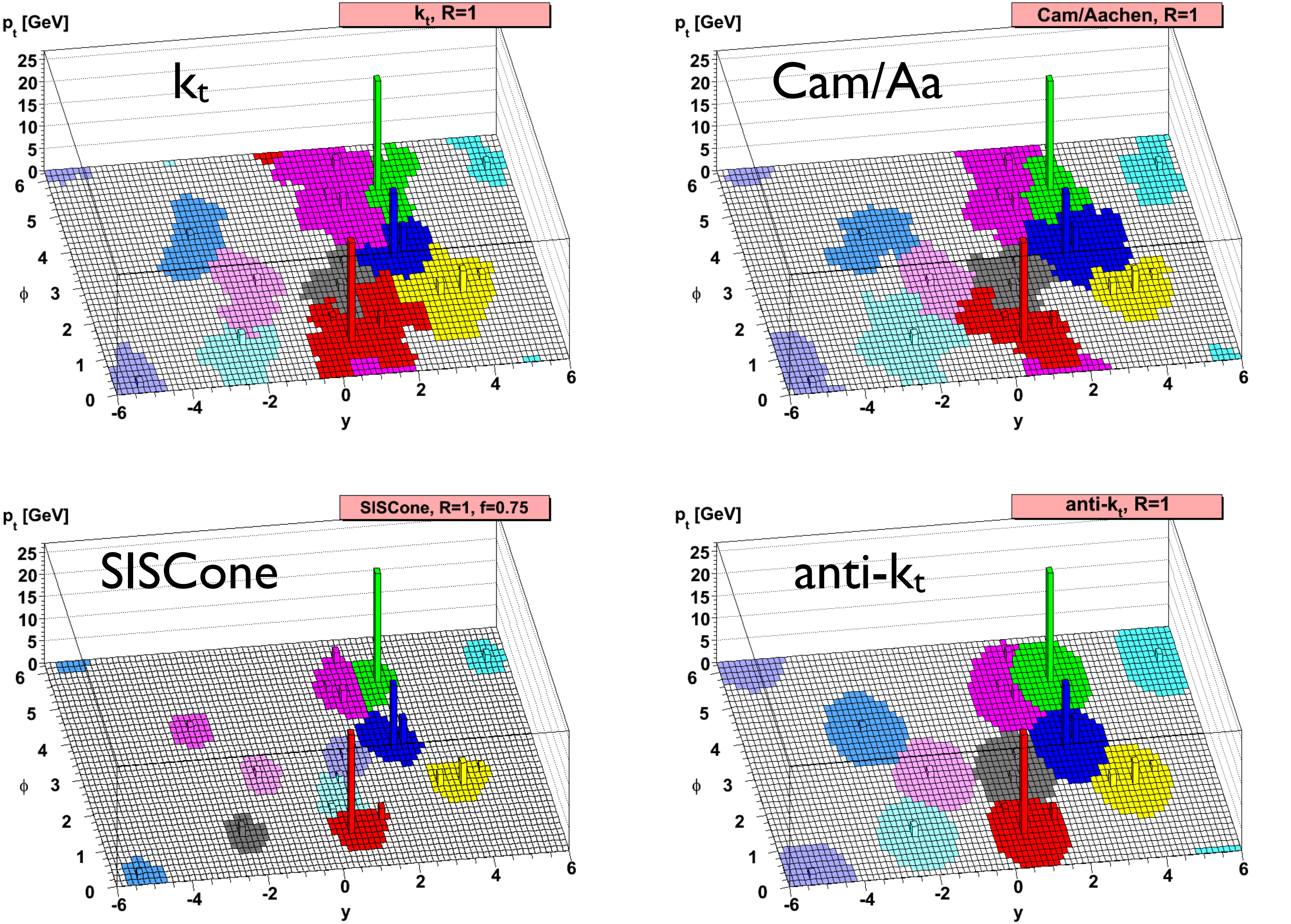
IRC safe algorithms

k_t	SR $d_{ij} = \min(p_{ti}^2, p_{tj}^2)\Delta R_{ij}^2/R^2$ hierarchical in rel p_t	Catani et al '91 Ellis, Soper '93	NlnN
Cambridge/ Aachen	SR $d_{ij} = \Delta R_{ij}^2/R^2$ hierarchical in angle	Dokshitzer et al '97 Wengler, Wobish '98	NlnN
anti-k_t	SR $d_{ij} = \min(p_{ti}^{-2}, p_{tj}^{-2})\Delta R_{ij}^2/R^2$ gives perfectly conical hard jets	MC, Salam, Soyez '08 (Delsart, Loch)	$N^{3/2}$
SISCone	Seedless iterative cone with split-merge gives 'economical' jets	Salam, Soyez '07	$N^2\ln N$

'second-generation' algorithms

All are available in FastJet, http://fastjet.fr

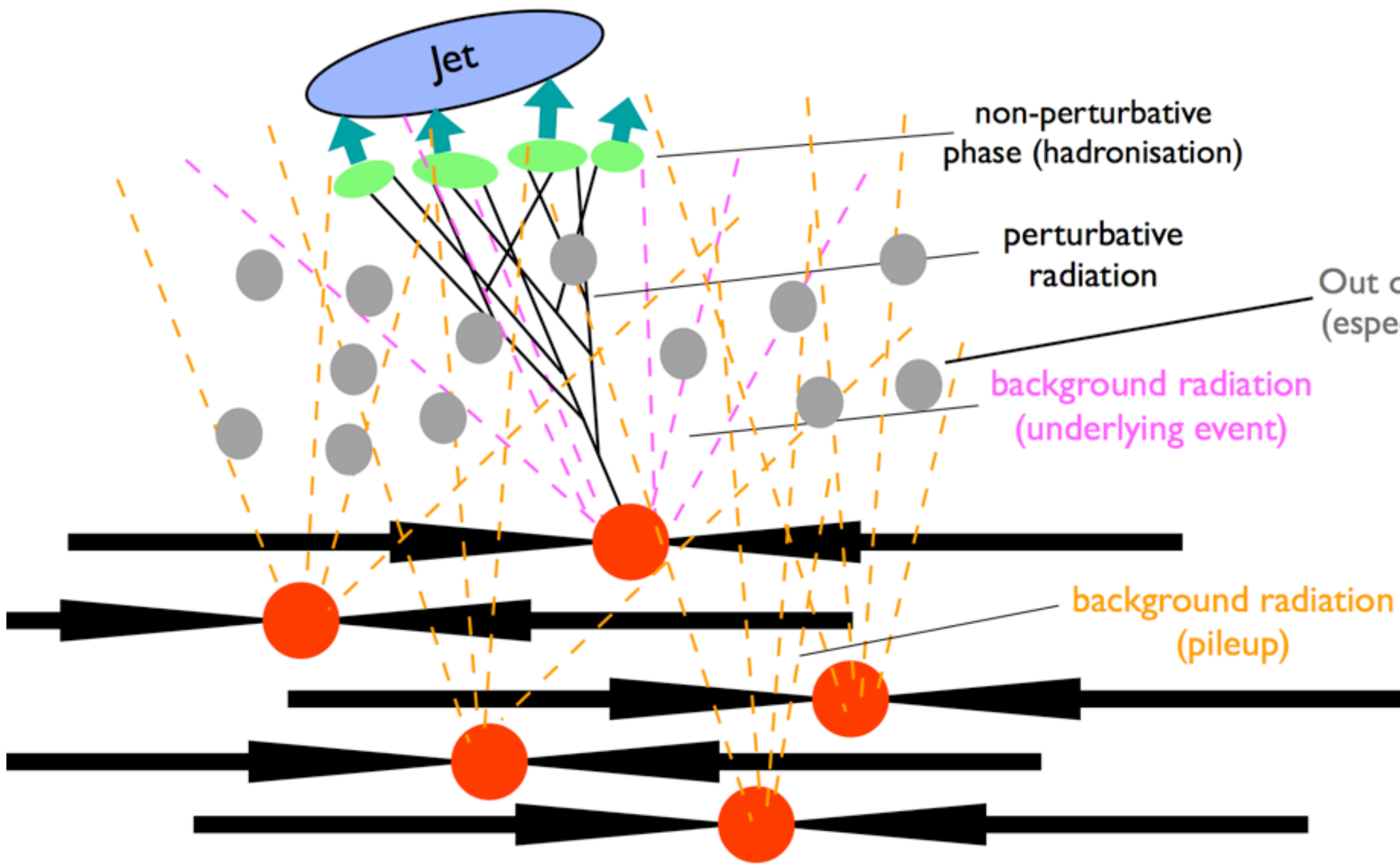
(As well as many IRC unsafe ones)



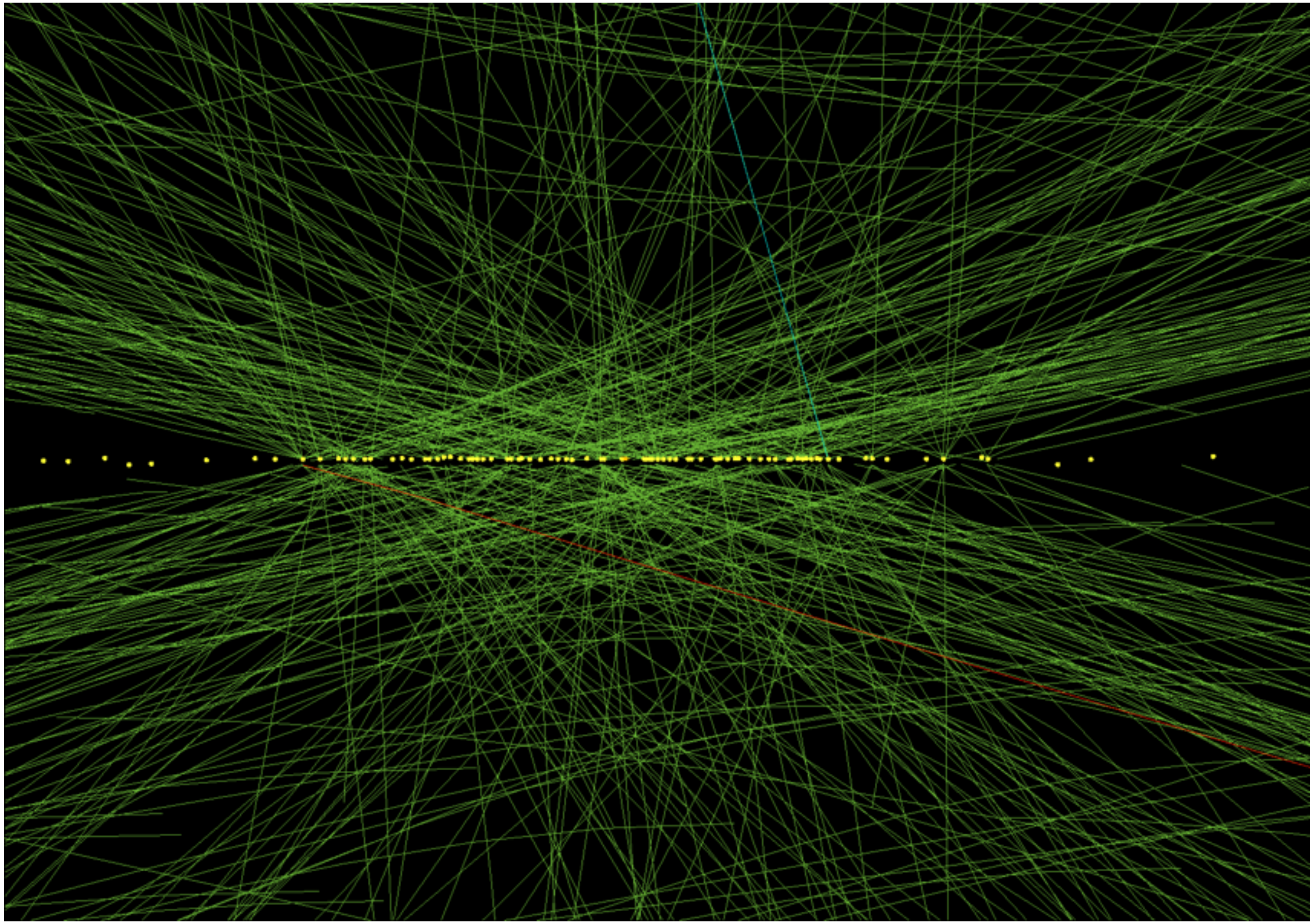
kt, R=1
kt
Cam/Aachen, R=1
Cam/Aa
SISCone, R=1, f=0.75
SISCone
anti-kt, R=1
anti-kt
pt [GeV]
φ
y

Background

Many ‘things’ can be clustered into (or lost from) a jet other than what we want (typically, perturbative radiation from a parton)



Ideally we’d like to be able to correct for these effects



78-vertices event from CMS

https://cds.cern.ch/record/1479324

Pileup can deposit several tens of GeV (or even hundreds, in a heavy ion collision) into a medium-sized jet

How are the hard jets modified by the background?

Susceptibility
(how much bkgd gets picked up)

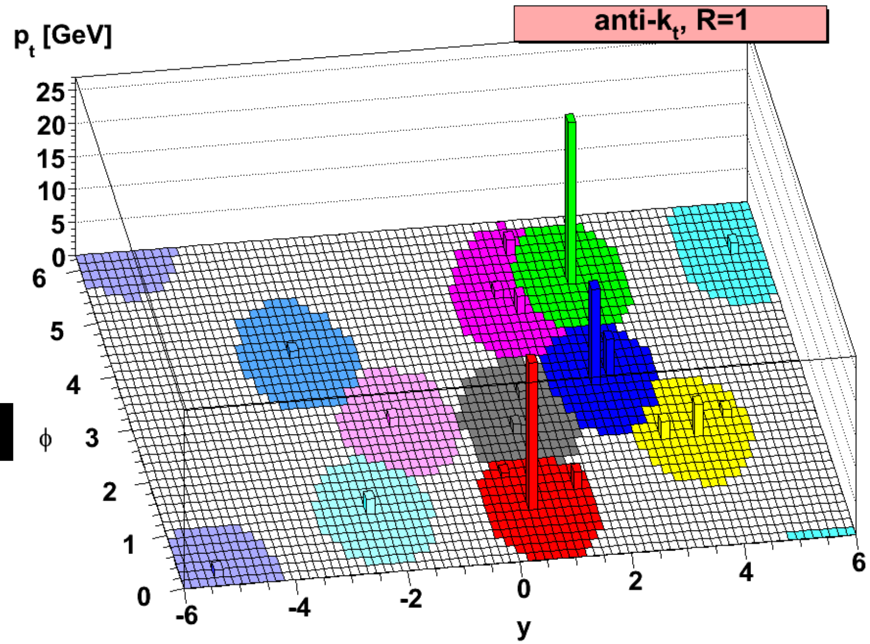
Jet areas

Resiliency
(how much the original jet changes)

Backreaction

Anti-k_t jets and background

Anti-k_t jets **maximise resiliency**, and their regular shapes makes them **easier to correct for detector-related effects**

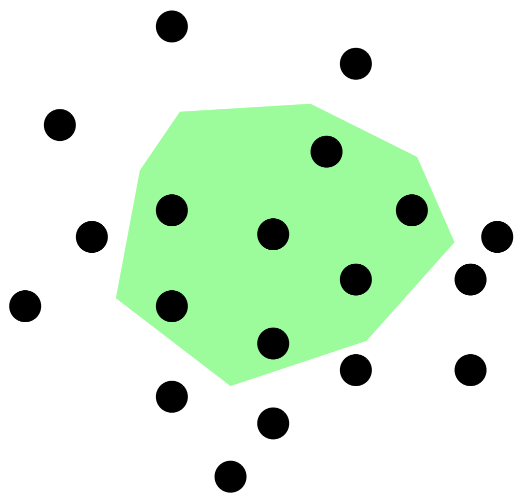


Default choice of all LHC collaborations

Resiliency: backreaction

"How (much) a jet changes when immersed in a background"

Without background



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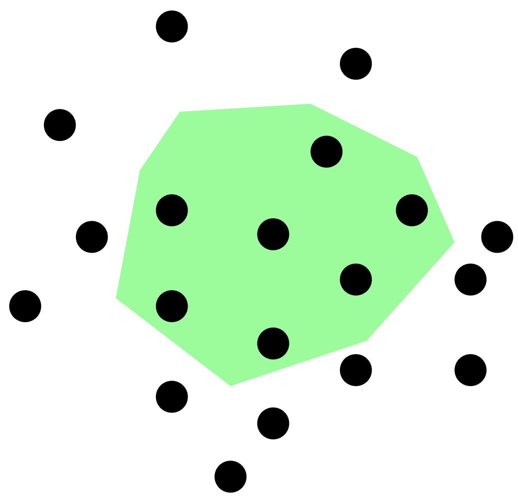

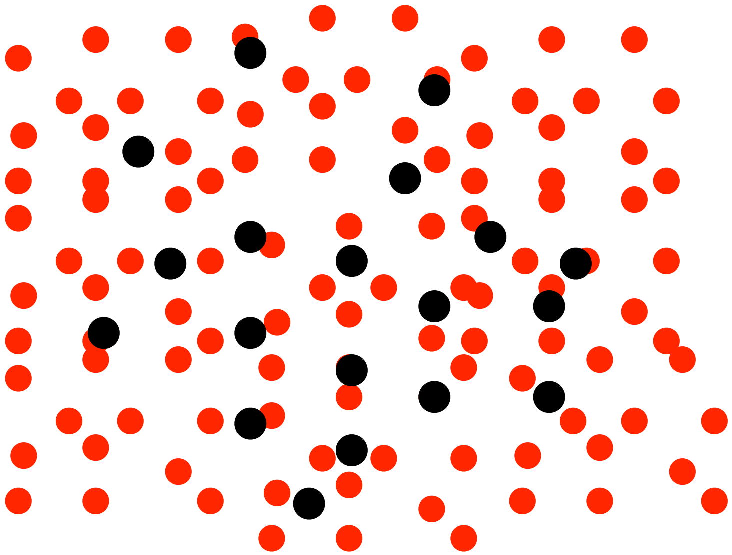

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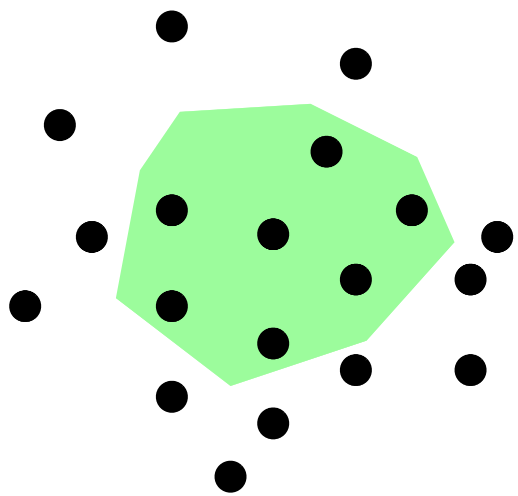
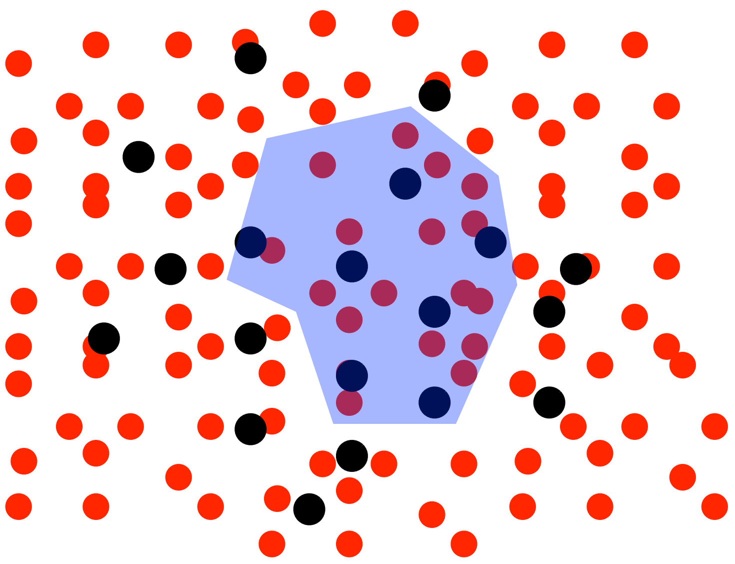


With background



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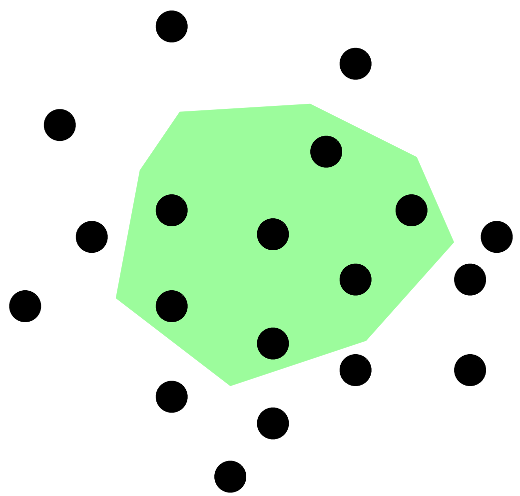
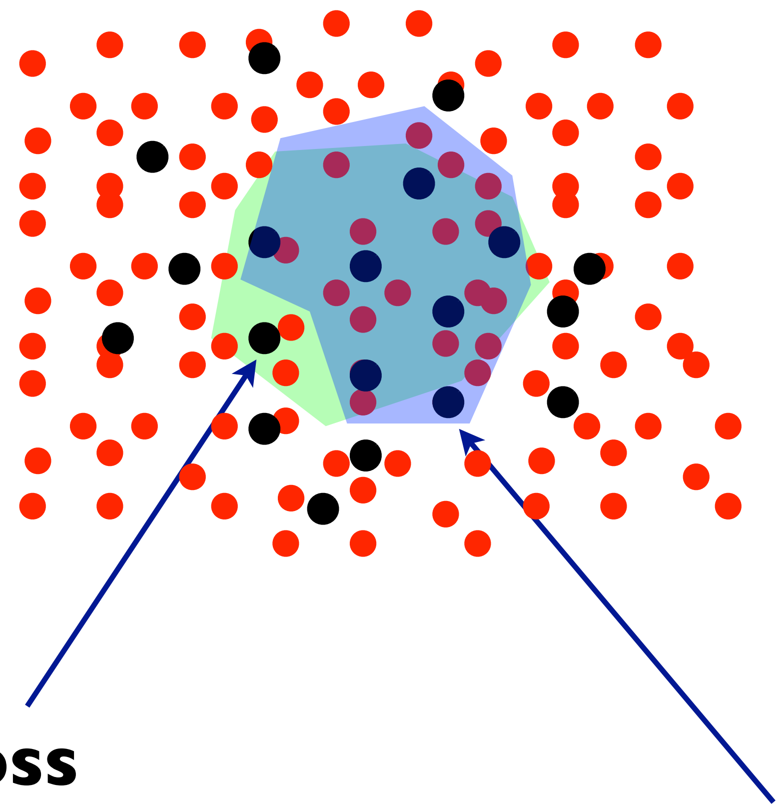


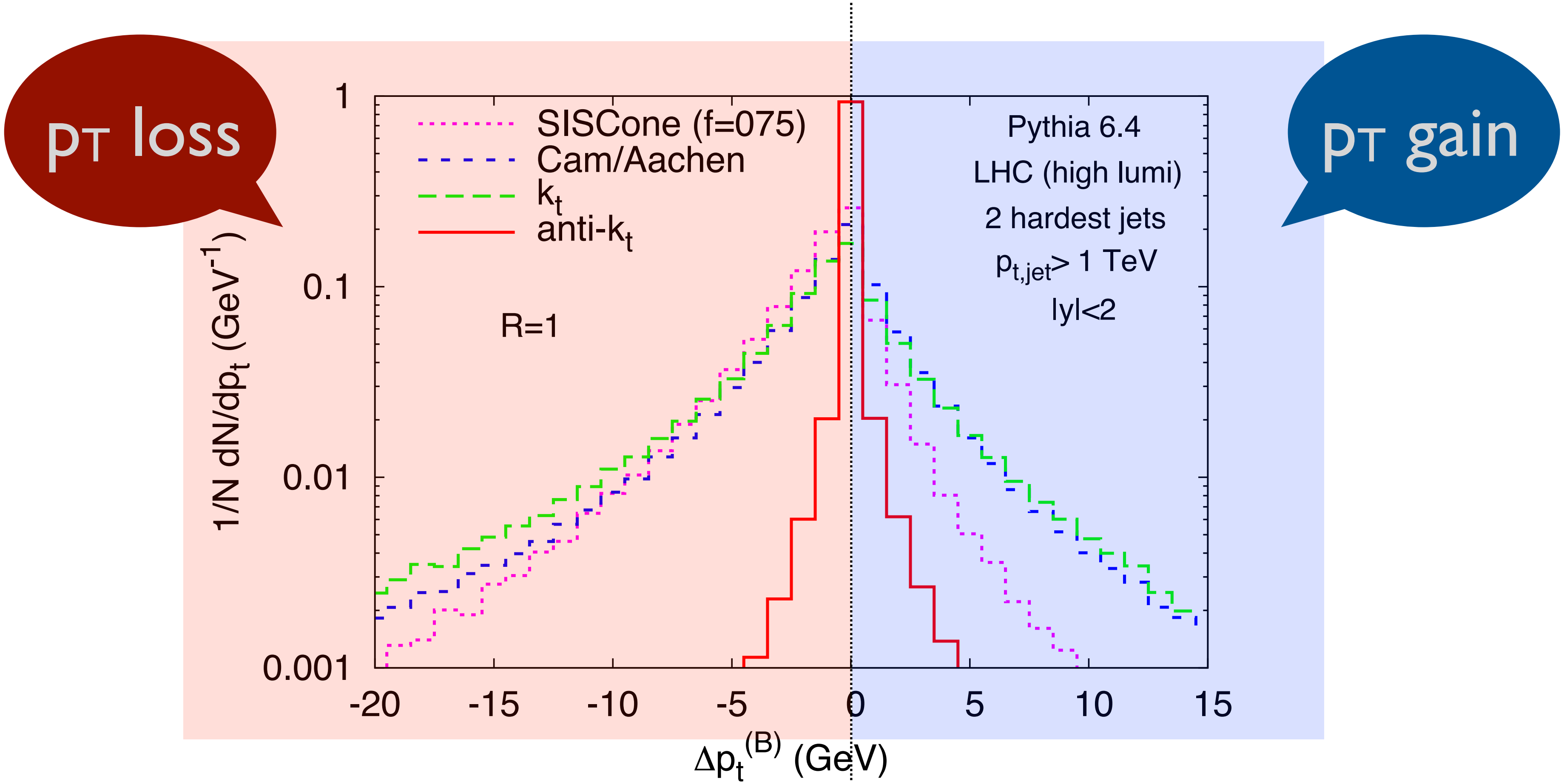
With background



Backreaction **loss**

Backreaction **gain**

Resiliency: backreaction



Anti-k_t jets are much more resilient to changes from background immersion

(NB. Backreaction is a minimal issue in pp background and at large pt.
Can be much more important in Heavy Ion collisions)

Hard jets and background

Modifications of the hard jet

$$\Delta p_t = \rho A \pm \left(\sigma\sqrt{A} + \sigma_\rho A + \rho\sqrt{\langle A^2\rangle - \langle A\rangle^2}\right) + \Delta p_t^{BR}$$

Background momentum density (per unit area)

background

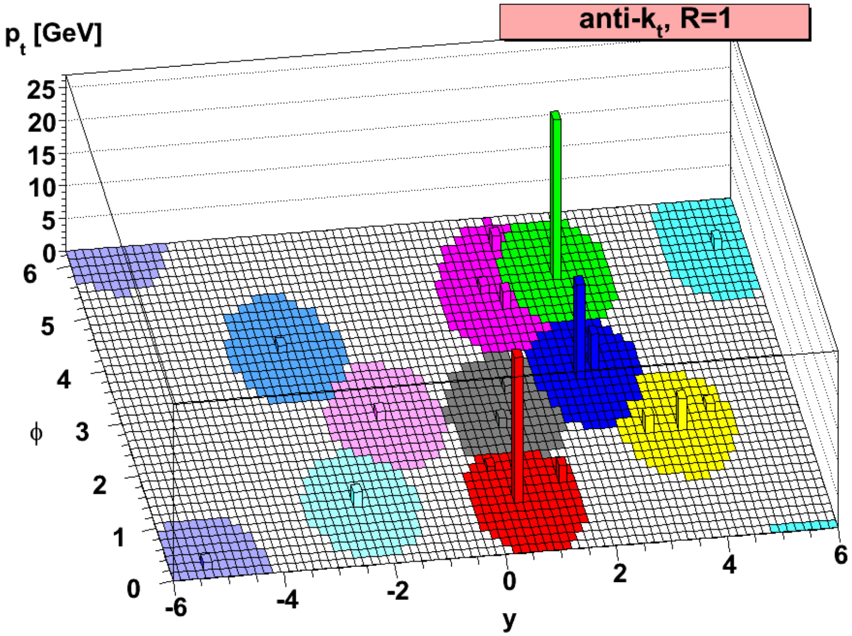
'susceptibility'

back-reaction

'resiliency'

Jet areas

Jet ***areas***, graphically represented by the coloured regions, represent the ***susceptibility*** of each jet to contamination from ***diffuse, soft radiation***



Given an IRC-safe jet algorithm, jet areas can be calculated numerically for each jet, opening the way for a jet-by-jet, rather than average, correction for background contamination

Background subtraction

Observable level

- Determination of *susceptibility to contamination* of each specific observable needed
- Possibility to get unbiased subtraction by construction
- Basic example: transverse momentum
  $\mathbf{p_t^{sub} = p_t^{raw} - \rho A}$ (MC, Salam 0707.1378)

- Other examples:
  - Analytical calculations of susceptibility for selected jet shapes (Sapeta et al. 1009.1143, Alon et al. 1101.3002)
  - Moments of jet fragmentation functions (MC, Quiroga, Salam, Soyez, 1209.6086)
  - Generic (numerical) approach to susceptibility determination for any shape (Soyet et al, 1211.2811)

Event (= particle) level

Background subtraction

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Event (= particle) level

- The event is modified before calculating observables (jets, shapes, etc)
- Method not naturally unbiased, but can often be tuned
- Final dispersion potentially lower, as effective number of particles usually reduced
- Examples:
  - CMS Voronoi method (Lai, unpubl.)
  - Cleansing (Krohn, Schwartz, Low, Wang, 1309.4777)
  - Constituent Subtraction (Berta, Spousta, Miller, Leitner, 1403.3108)
  - PUPPI (Bertolini, Harris, Low, Tran, unpubl.)
  - SoftKiller (MC, Salam, Soyez, 1407.0408)
  - ....

Background subtraction: jet-based

Correction of a jet transverse momentum

$$p_T^{\text{hard jet, corrected}} = p_T^{\text{hard jet, raw}} - \rho \times \text{Area}_{\text{hard jet}}$$

MC, Salam, 0707.1378

If ρ is measured on an event-by-event basis, and each jet subtracted individually, this procedure will remove many fluctuations and generally improve the resolution of, say, a mass peak

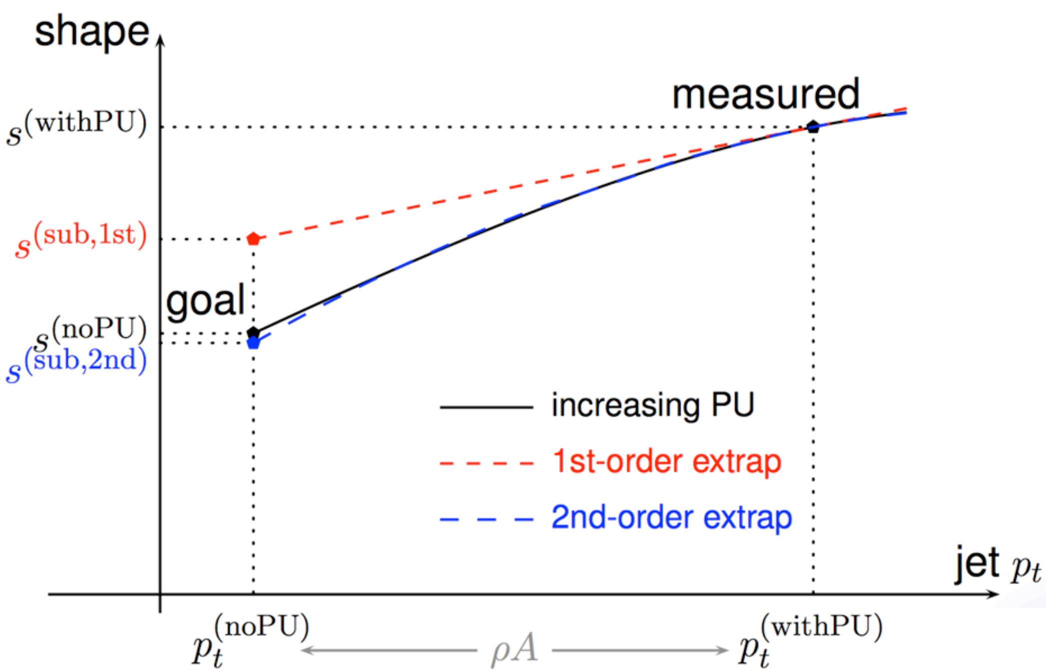
$$\Delta p_t = \rho A \pm (\sigma\sqrt{A} + \sigma_\rho A + \rho\sqrt{\langle A^2\rangle - \langle A\rangle^2}) + \Delta p_t^{BR}$$

Irreducible fluctuations: uncertainty of the subtraction

Needs two ingredients: ρ and A_{jet}

Numerical jet shape correction

Soyez et al. 1211.2811



A generic **jet shape**
(a function of the momenta of all constituents of a jet) is modified by the addition of pileup

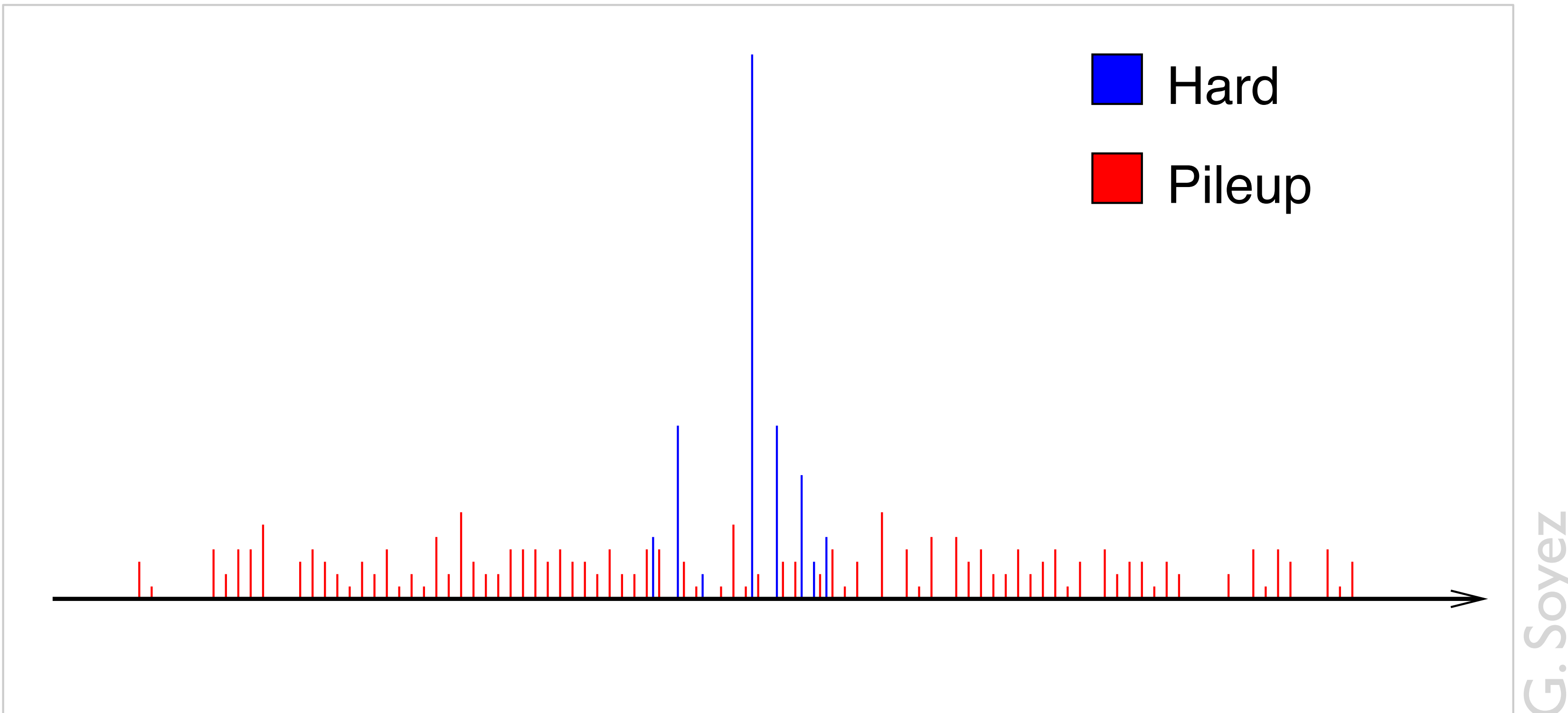
Correct it by calculating numerically the derivatives that enter its Taylor expansion and subtracting (this generalises the jet area/median subtraction for transverse mom.)

Pileup momentum density

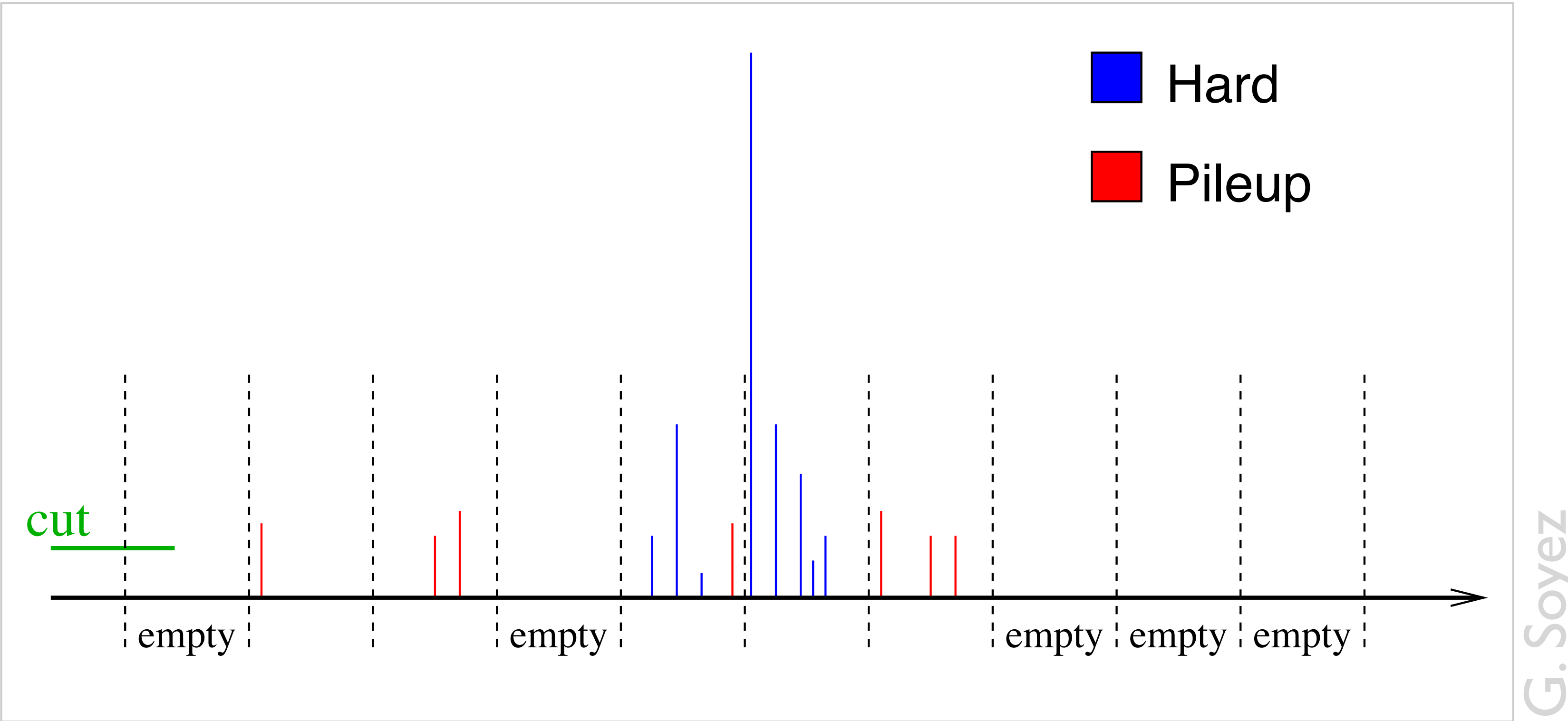
Numerical derivative w.r.t. ghosts momenta

$$V_{\text{jet,sub}} = V_{\text{jet}} - \rho V_{\text{jet}}^{[1]} + \frac{1}{2}\rho^2 V_{\text{jet}}^{[2]} + \cdots$$

An event: particle level



Soft Killer introduces a particle momentum cut such that the median momentum density (ρ) of the event is zero

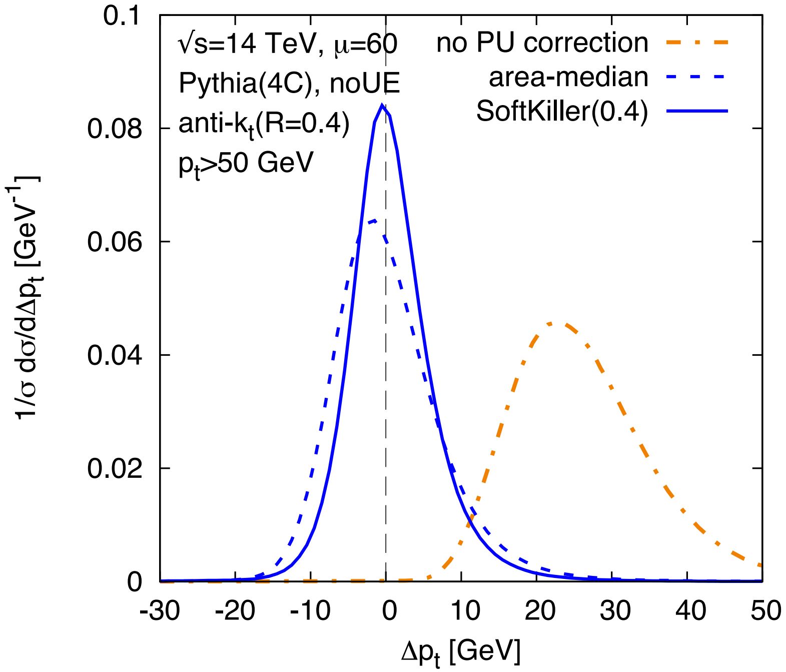


Half of the event is empty ⇒ **ρ = 0** (because it's the median)

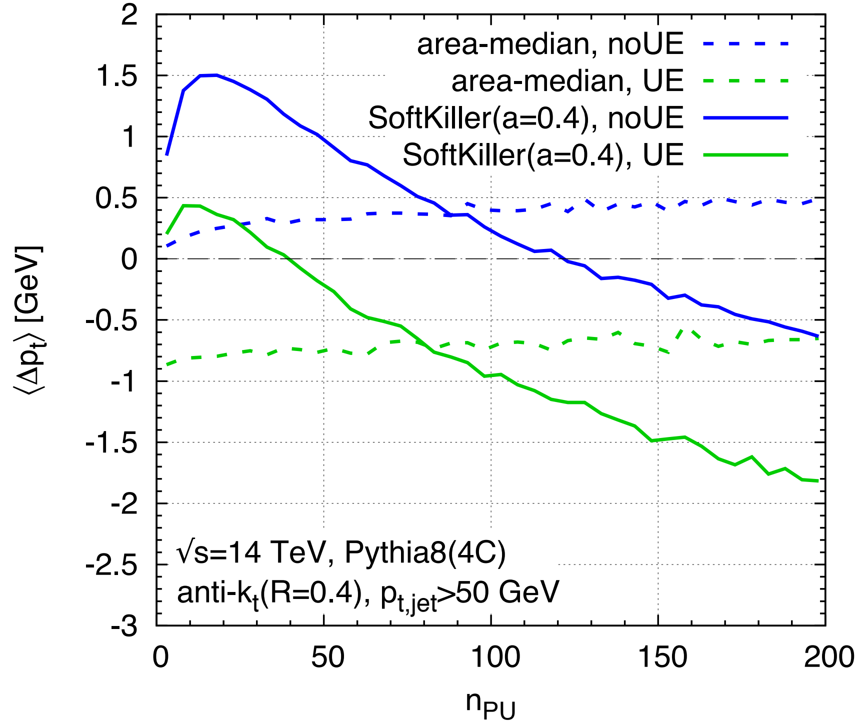
NB. SK needs tuning of the size of the patches used to calculate ρ.
0.4 was found to be a good choice for R=0.4 jets

Soft Killer performance

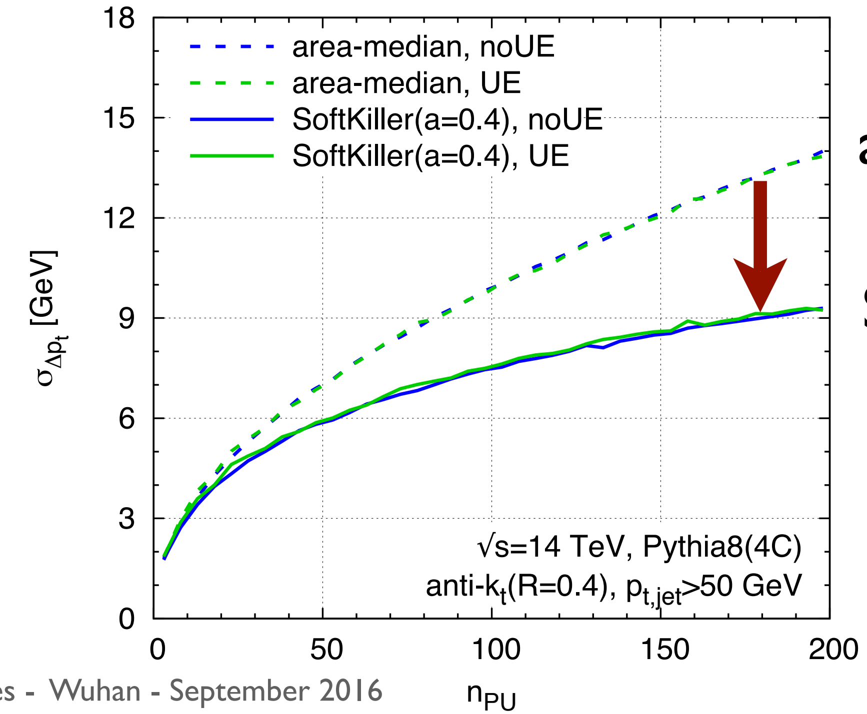
60 average PU events



p_t shift, Δp_t



Δp_t

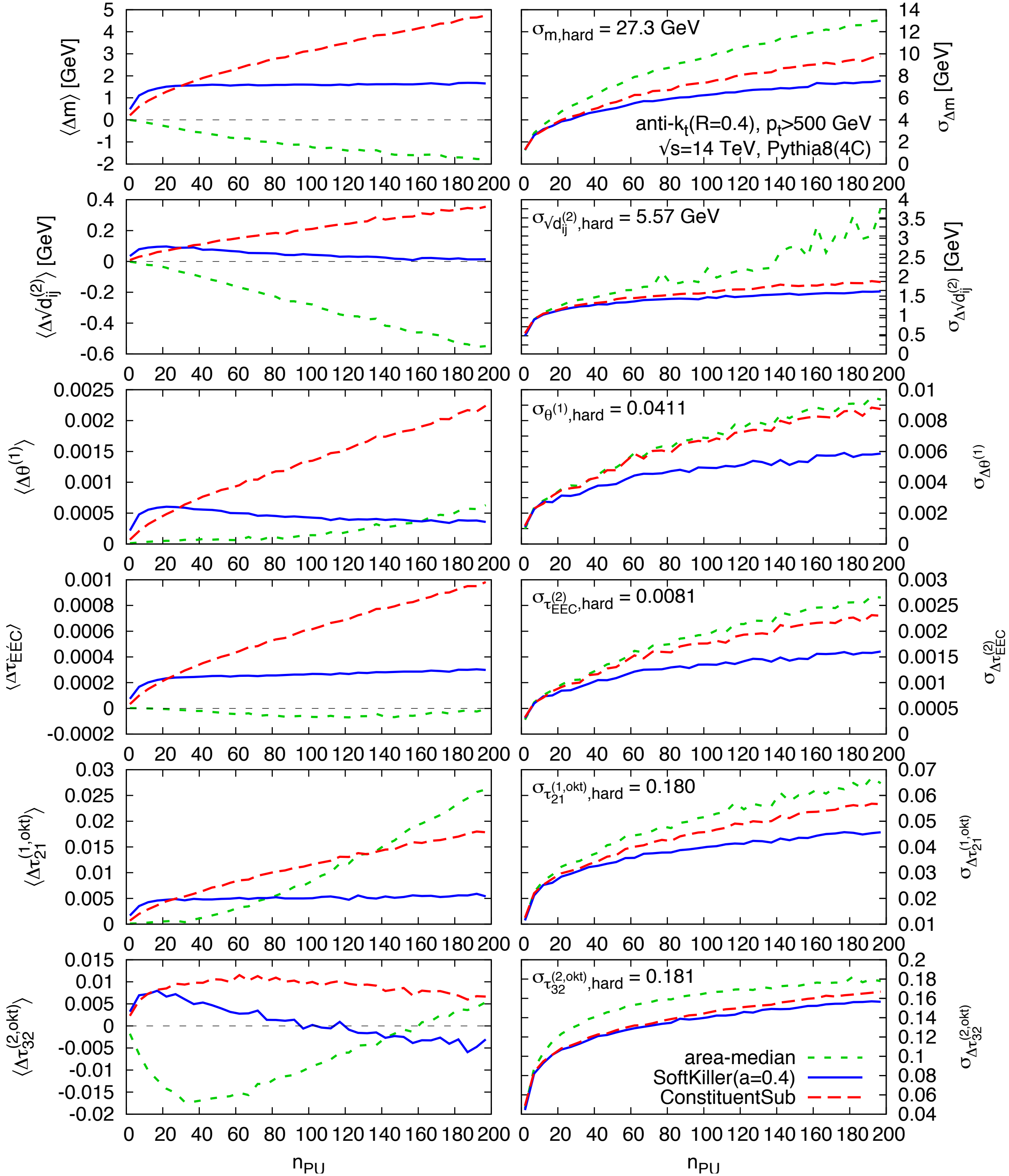


area-median

Soft Killer

$\sigma_{\Delta pt}$

Soft Killer performance



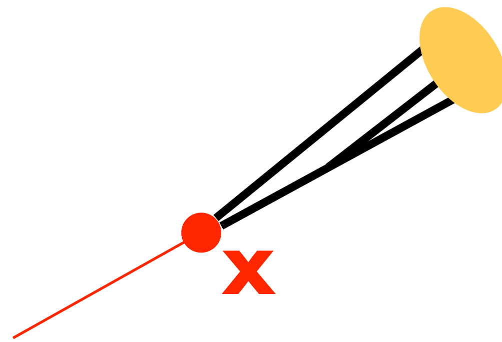
Many jet shapes:

- jet mass
- kt clustering scale
- jet width (= broadening, = girth)
- energy-energy correlation moment
- τ_{21} and τ_{32} N-subjettiness ratios

- Biases under control
- Dispersions smaller than with other methods

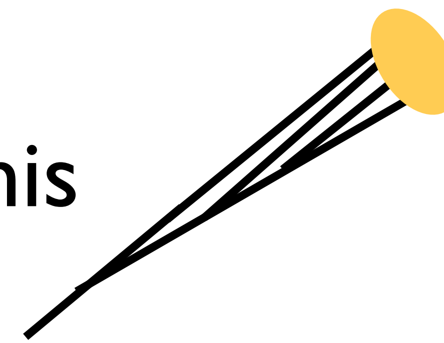
Not all jets are created equal

For instance, you may want to be able to tell



Decay of a heavy (boosted) object

from this



Light parton fragmentation

Or, more generally, you may want to be able to tell something about how the jet originated (e.g. quark/gluon discrimination, quenching, ...)

How to ‘look’ inside a jet?

- Use the clustering history of a ‘physical’ hierarchical clustering algorithm
- Define jet shape-variables sensitive to specific distribution of radiation inside the jet
- Literally ‘look’ at the distribution of radiation inside the jet (machine-learning techniques)
- .....

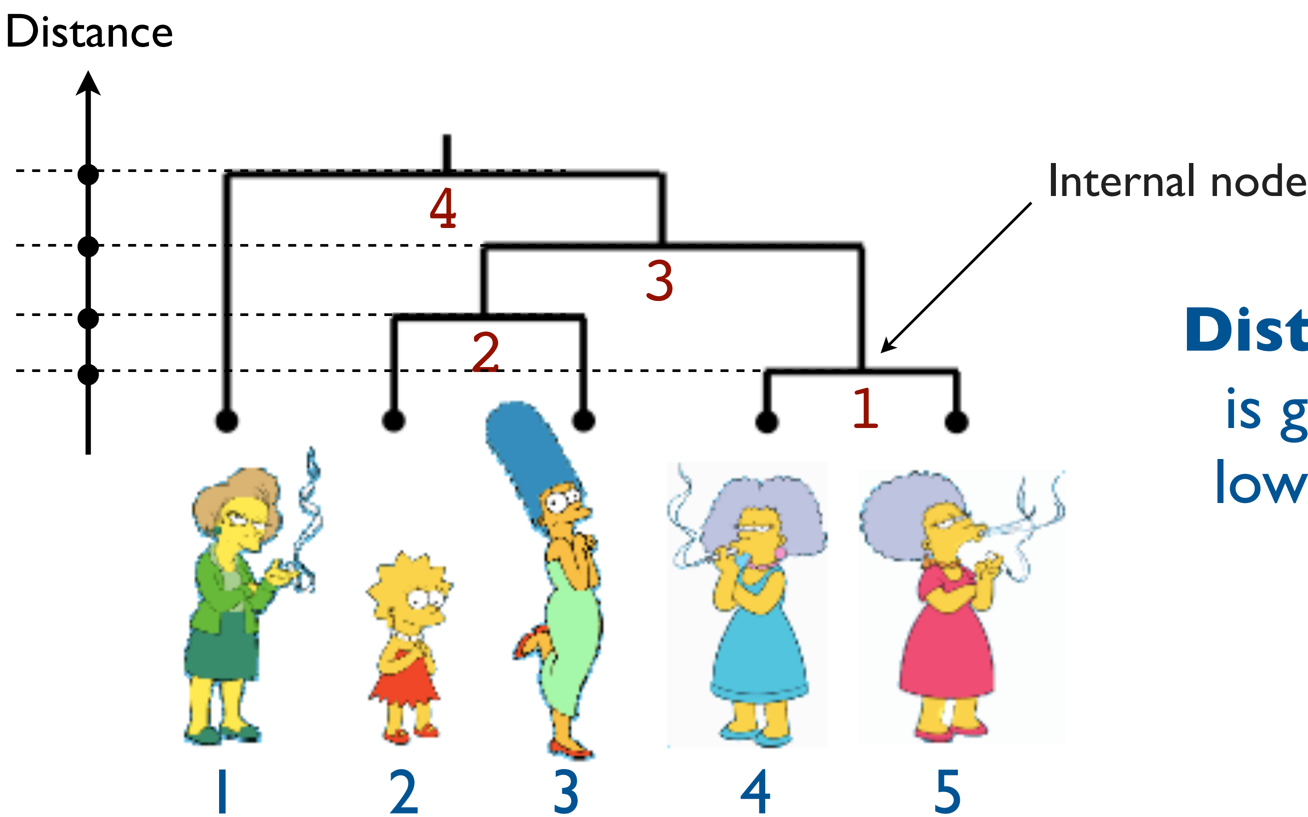
Tagging and Grooming

- The substructure of a jet can be exploited to
  - ***tag*** *a particular structure inside the jet, i.e. a massive particle*
    - *First examples: Higgs (2-prong decay), top (3-prong decay)*
  - *remove background contamination from the jet or its components, while keeping the bulk of the perturbative radiation (often generically denoted as* ***grooming****)*
    - *First examples: filtering, trimming, pruning*

To understand how we need to recall how a sequential recombination algorithm works

Dendrogram

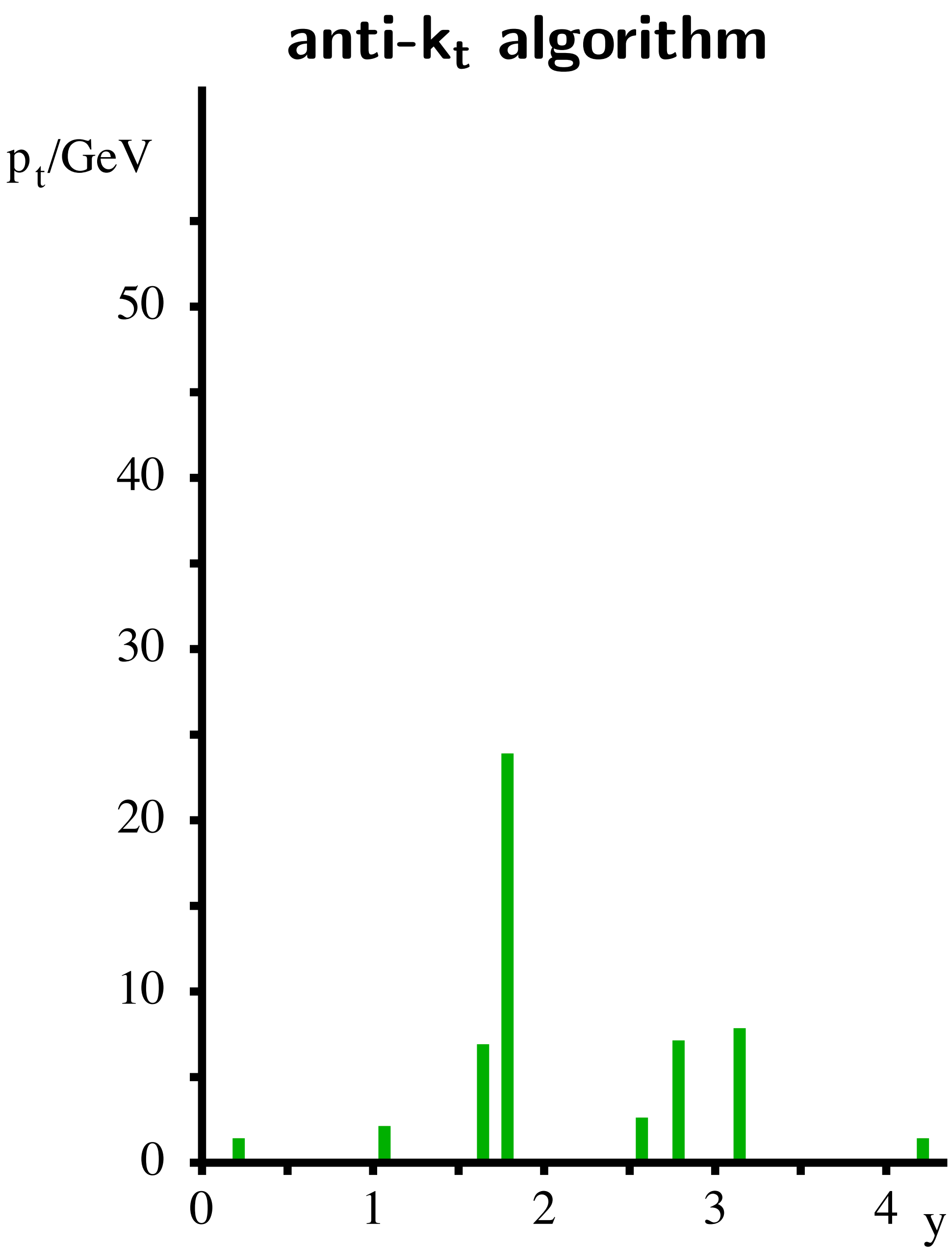
Used to represent graphically the sequence of clustering steps in a sequential recombination algorithm



Distance between two objects is given by the **height** of the lowest internal node that they share.

Order of clustering here is 1,2,3,4

The **clustering sequence** is 4-5 (1), 2-3 (2), 23-45 (3), 1-2345 (4) anti-kt



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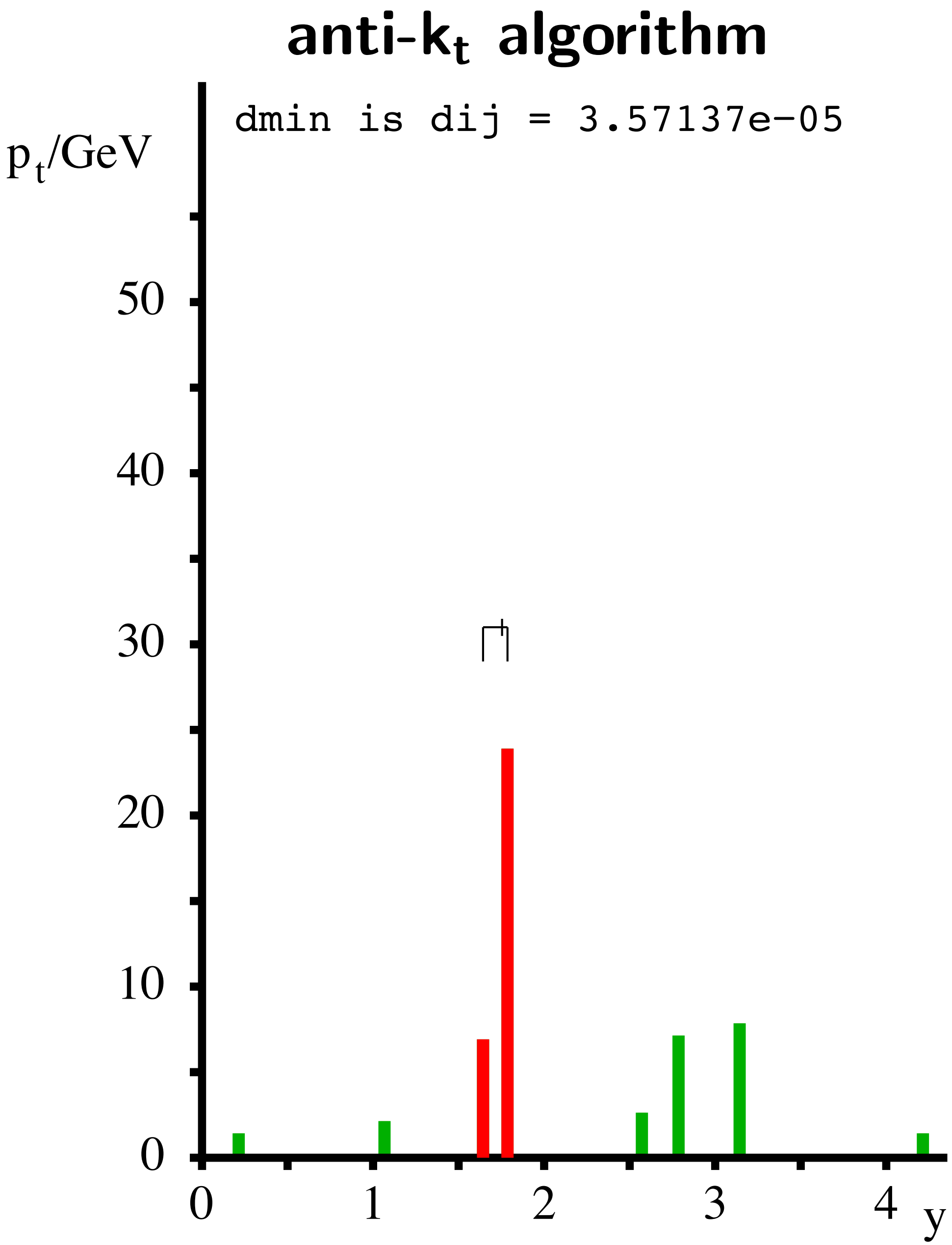
This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).



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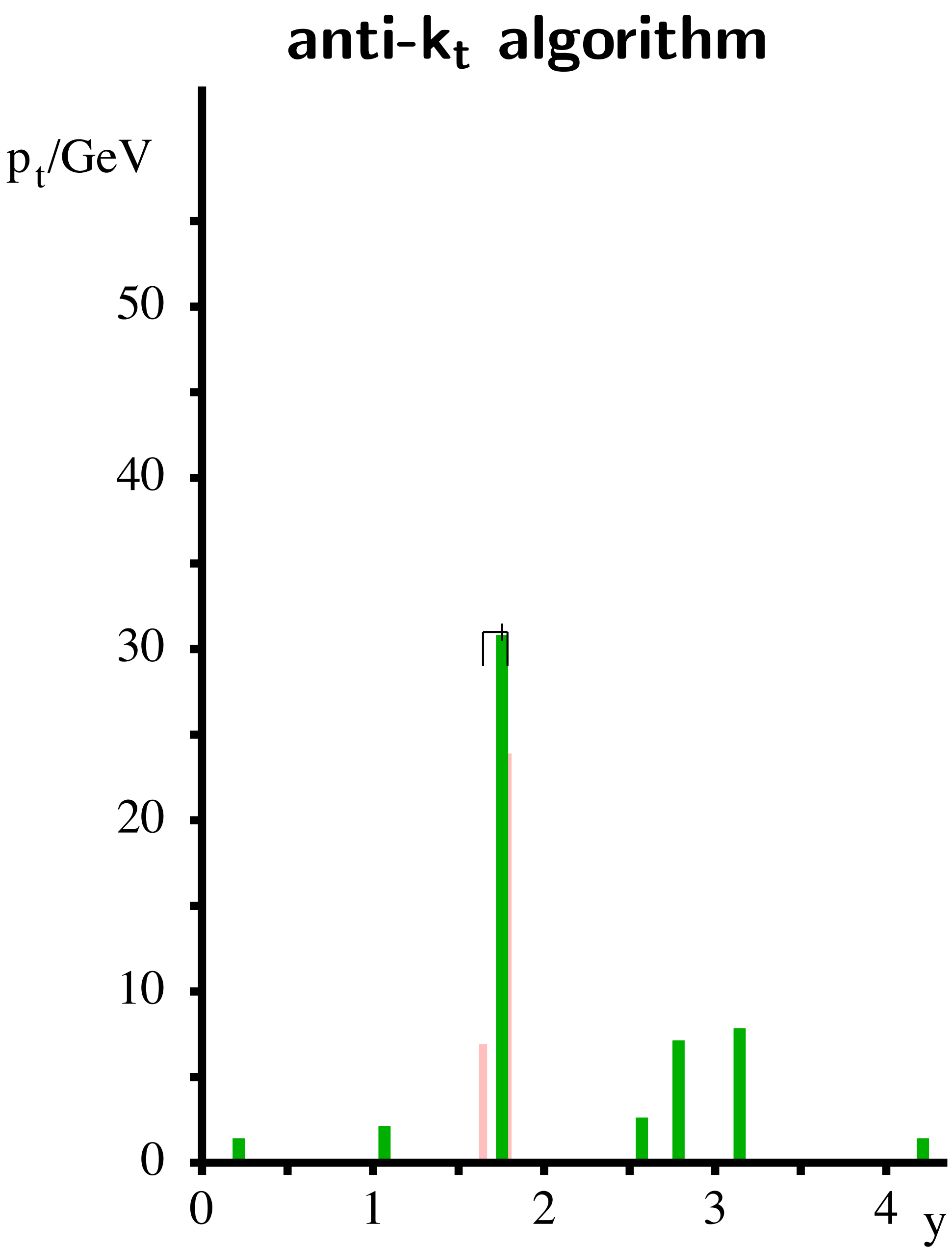

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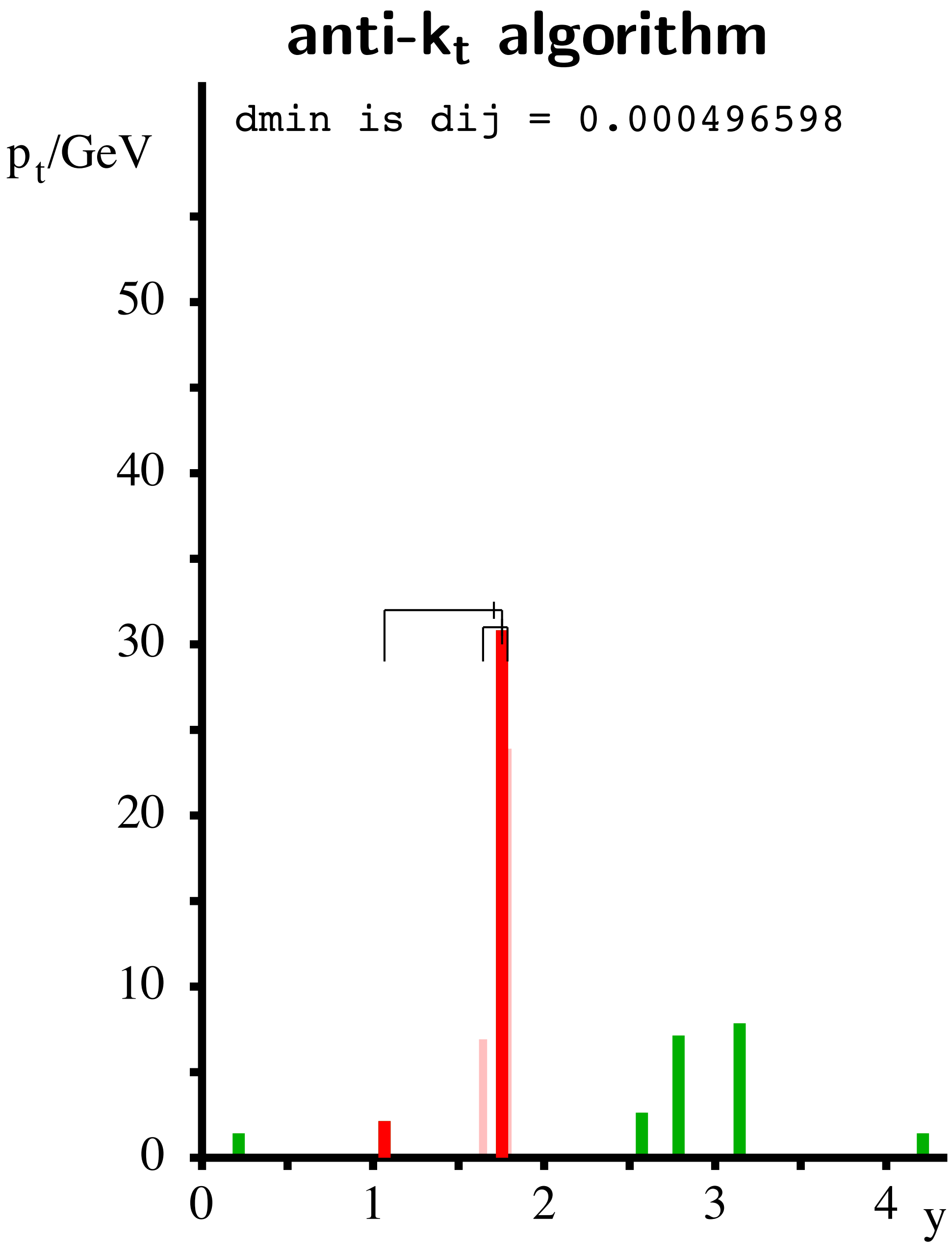

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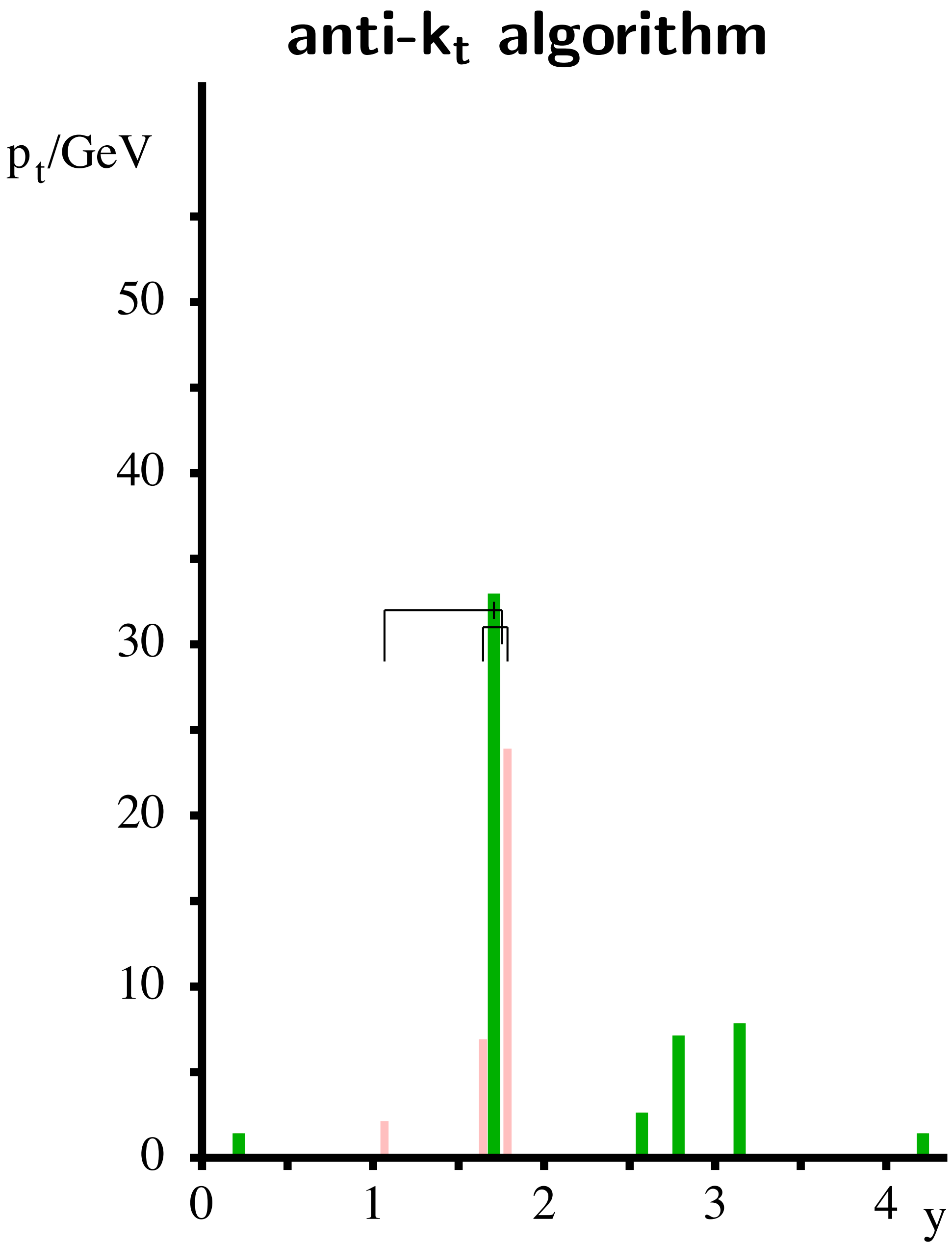

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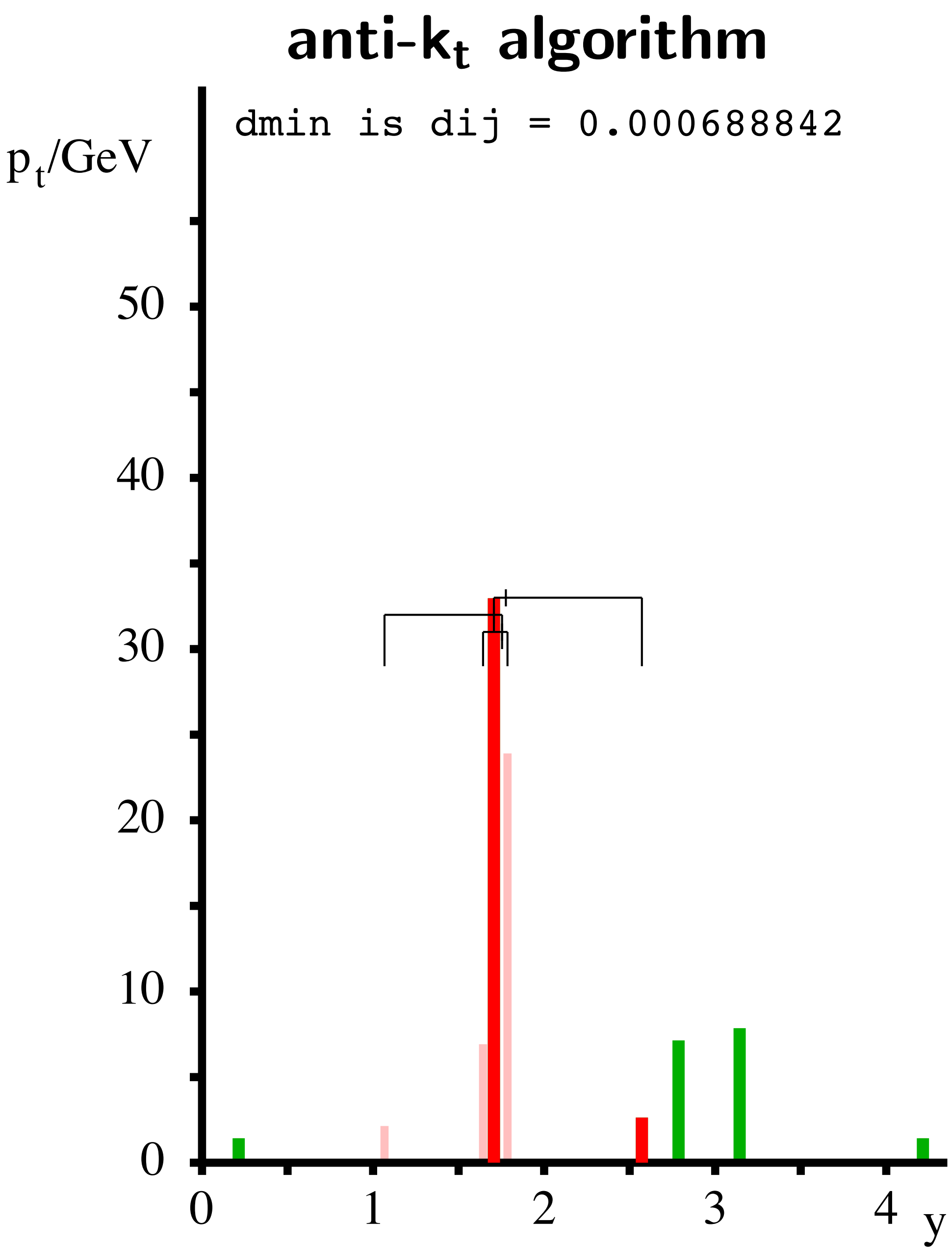

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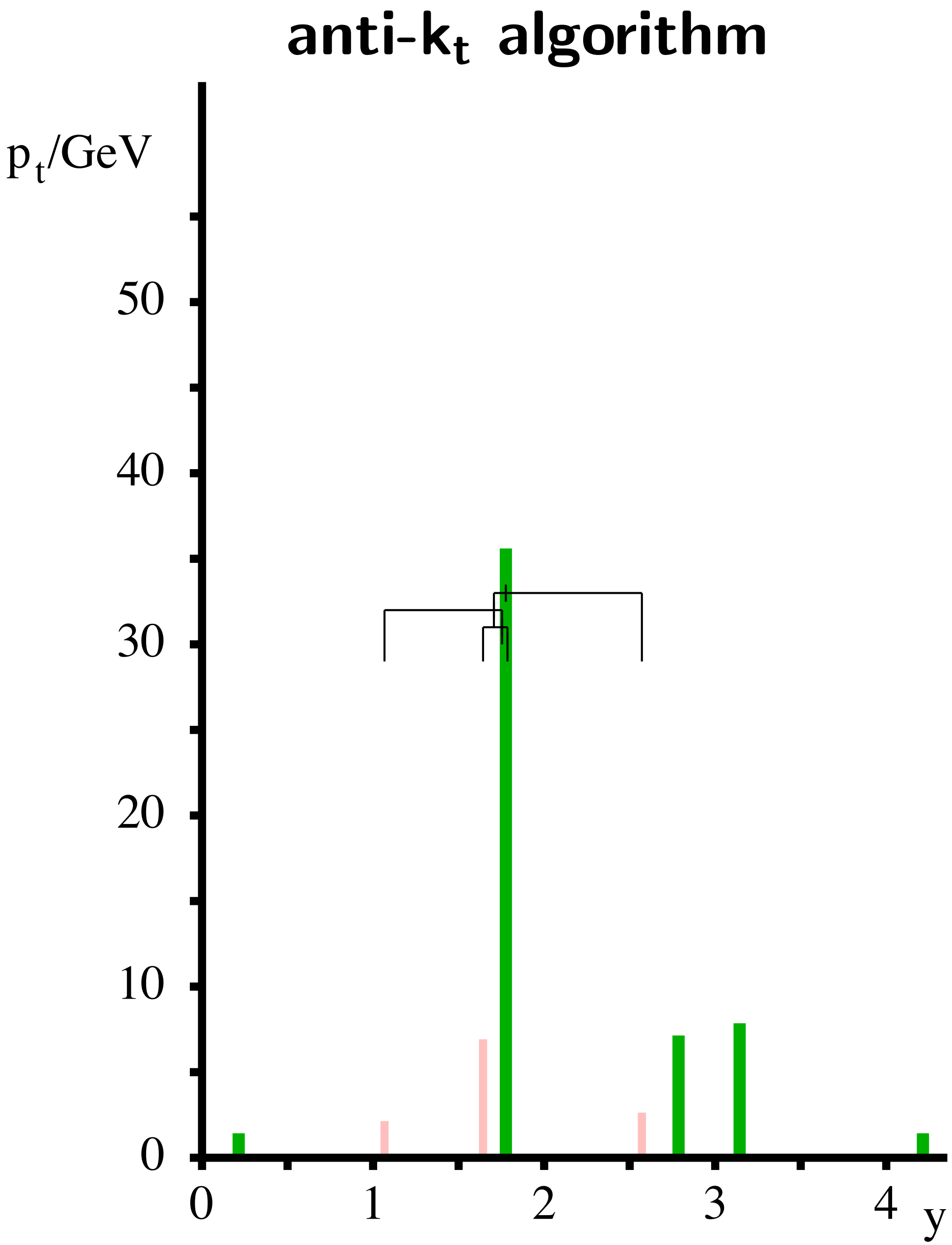

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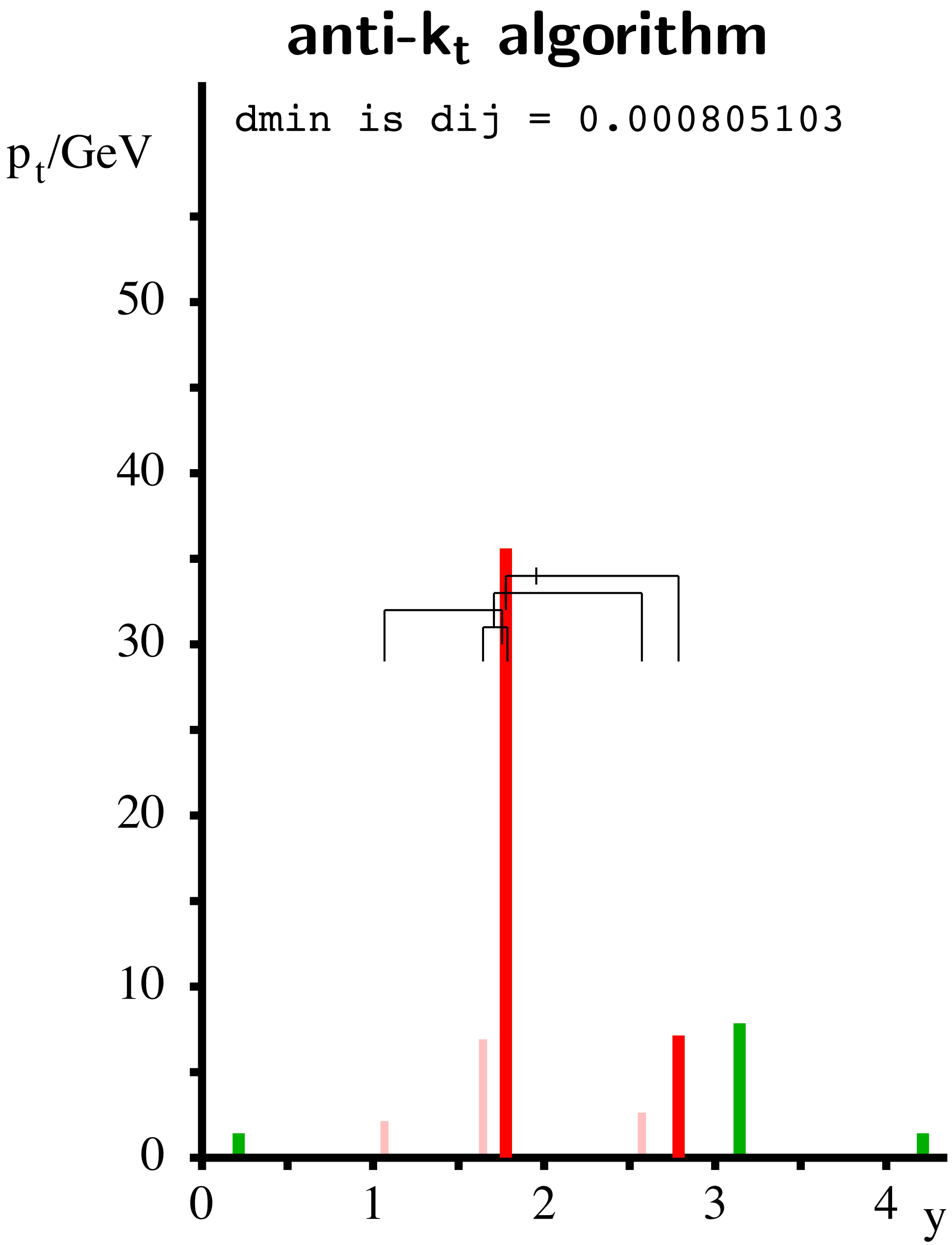

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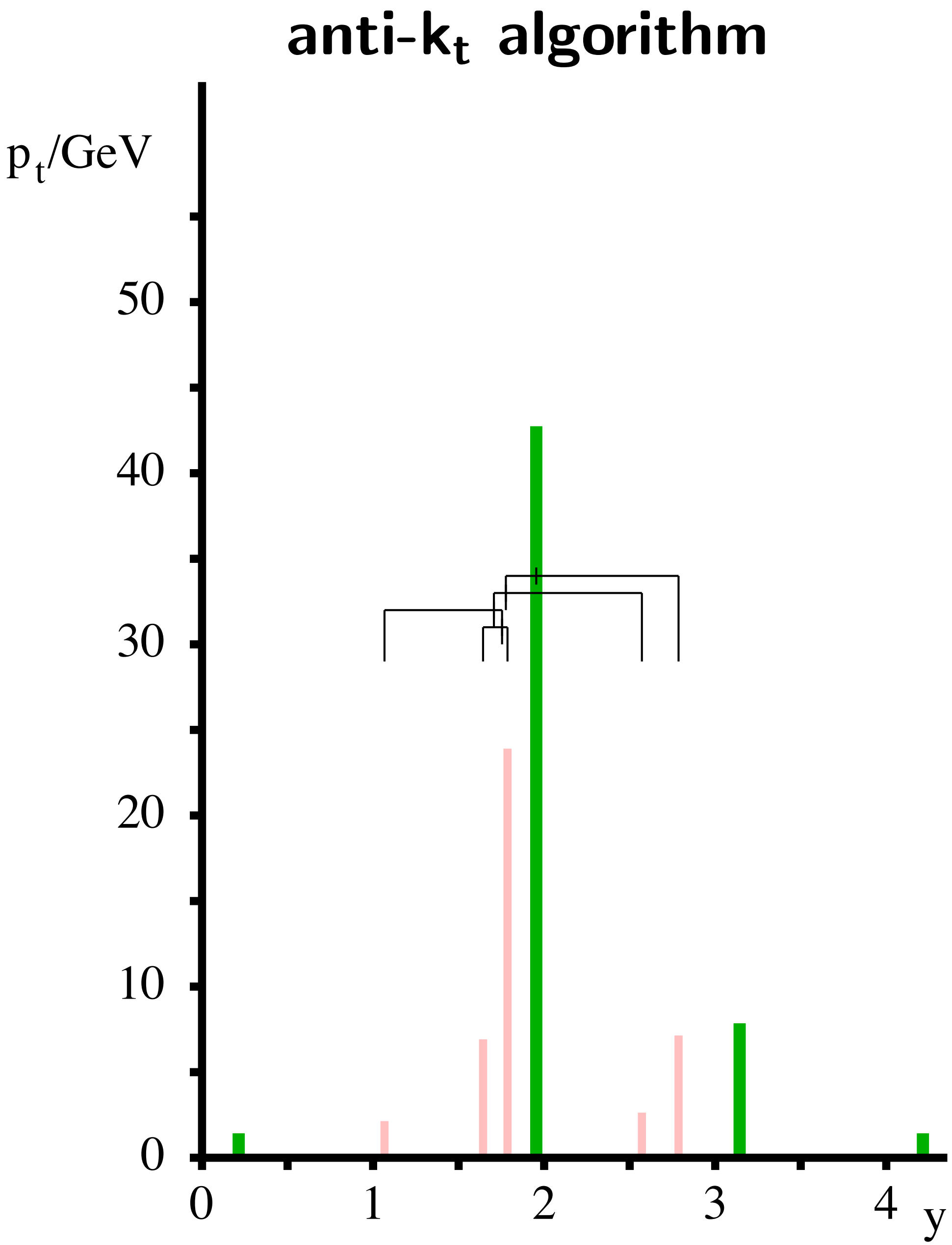

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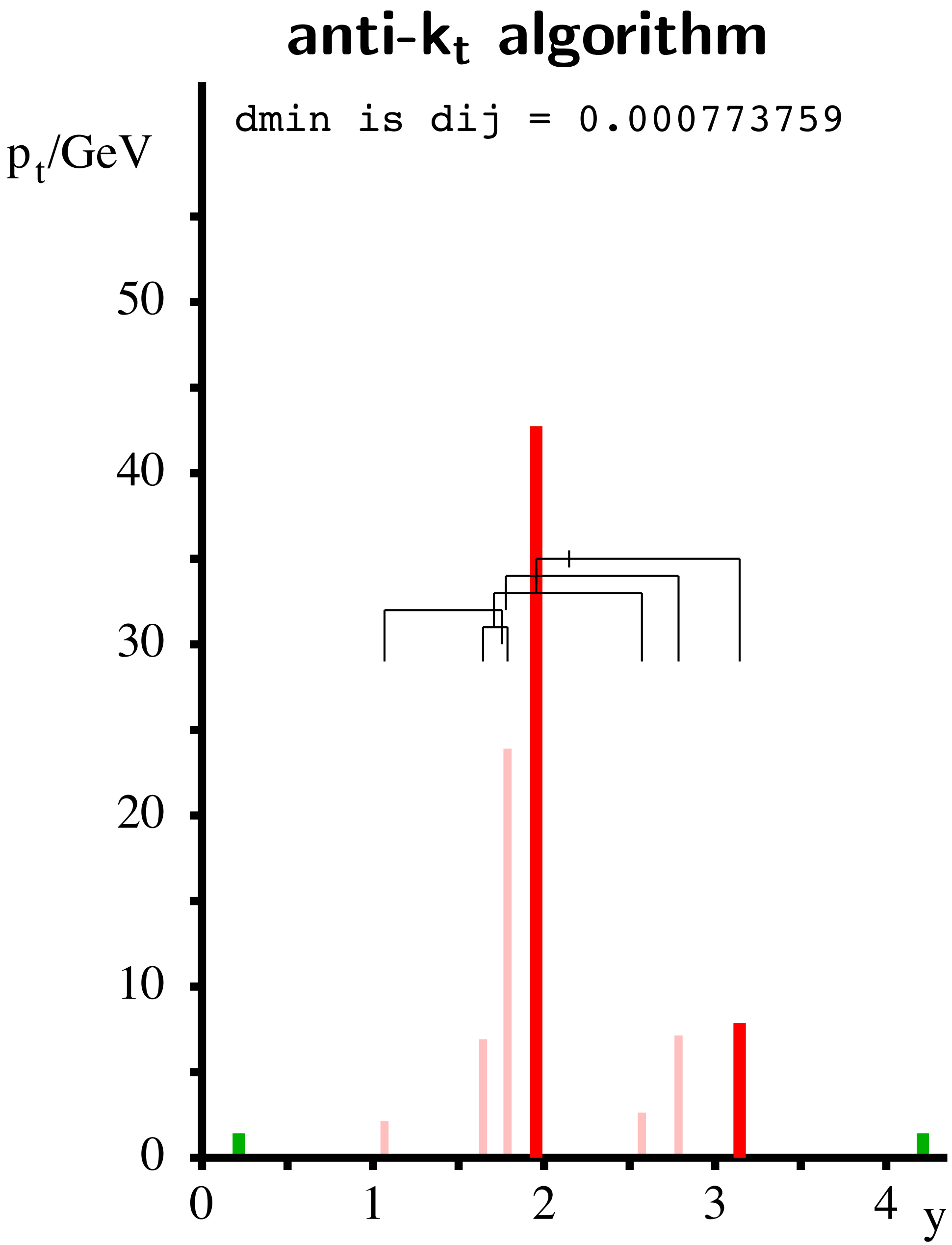

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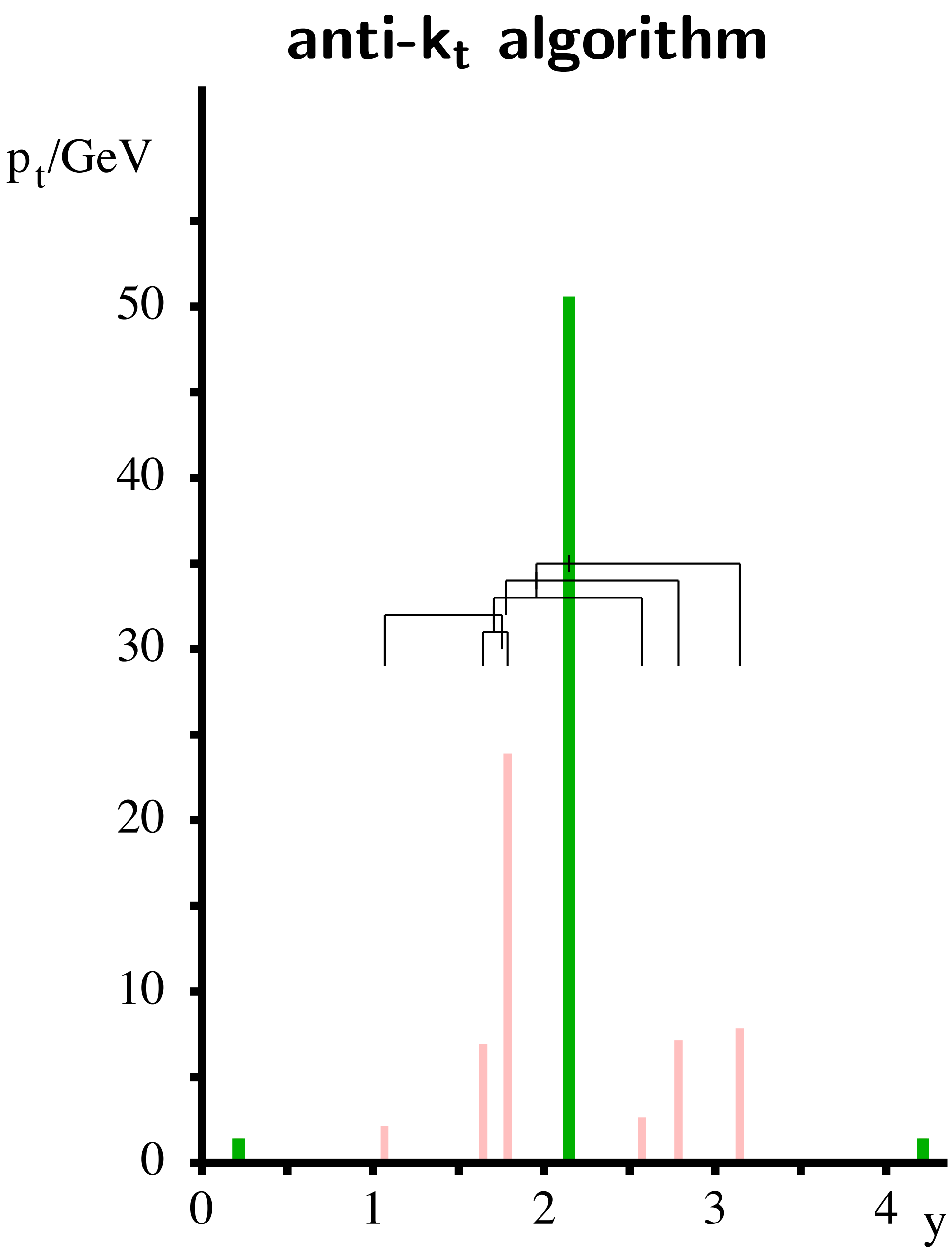

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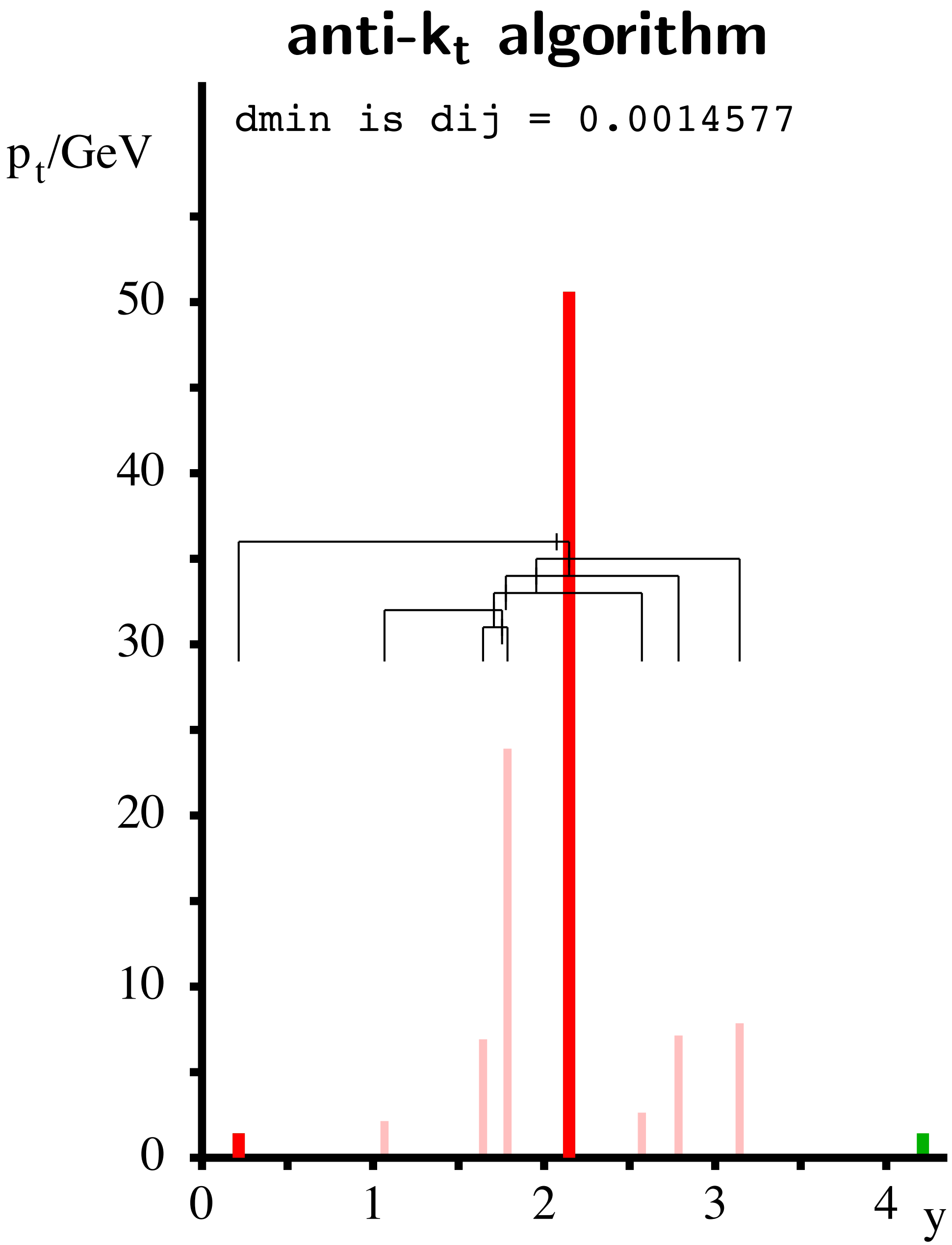

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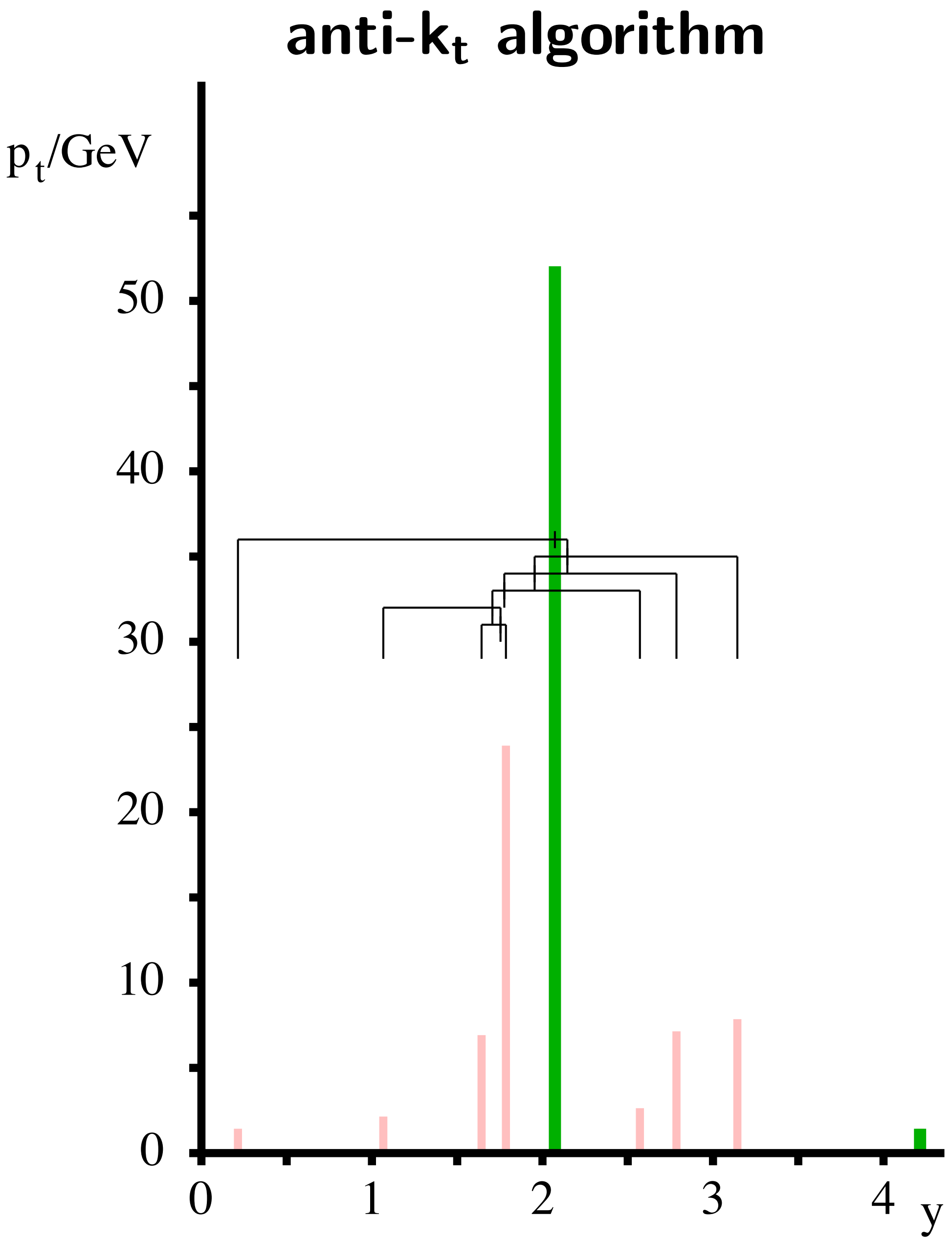

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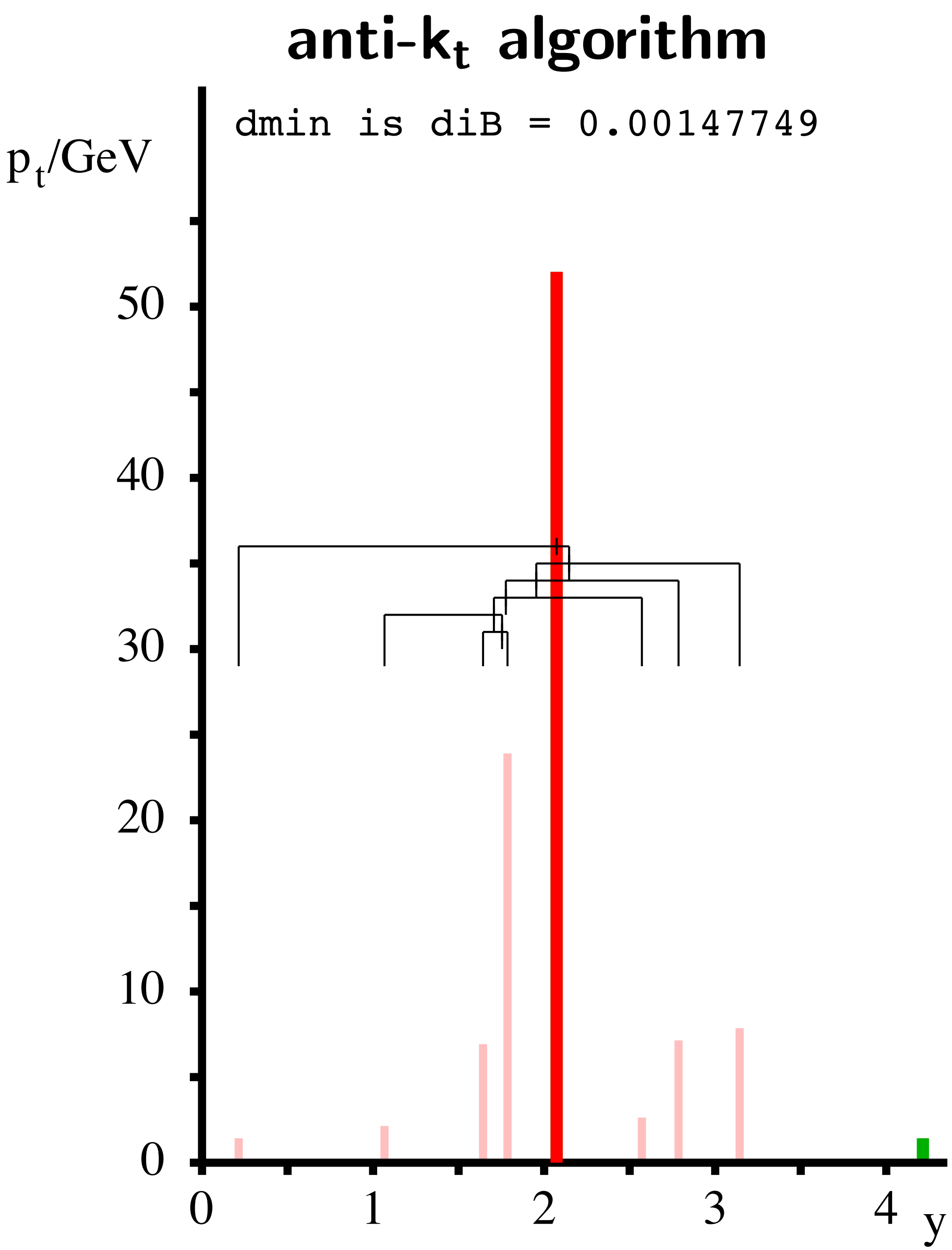

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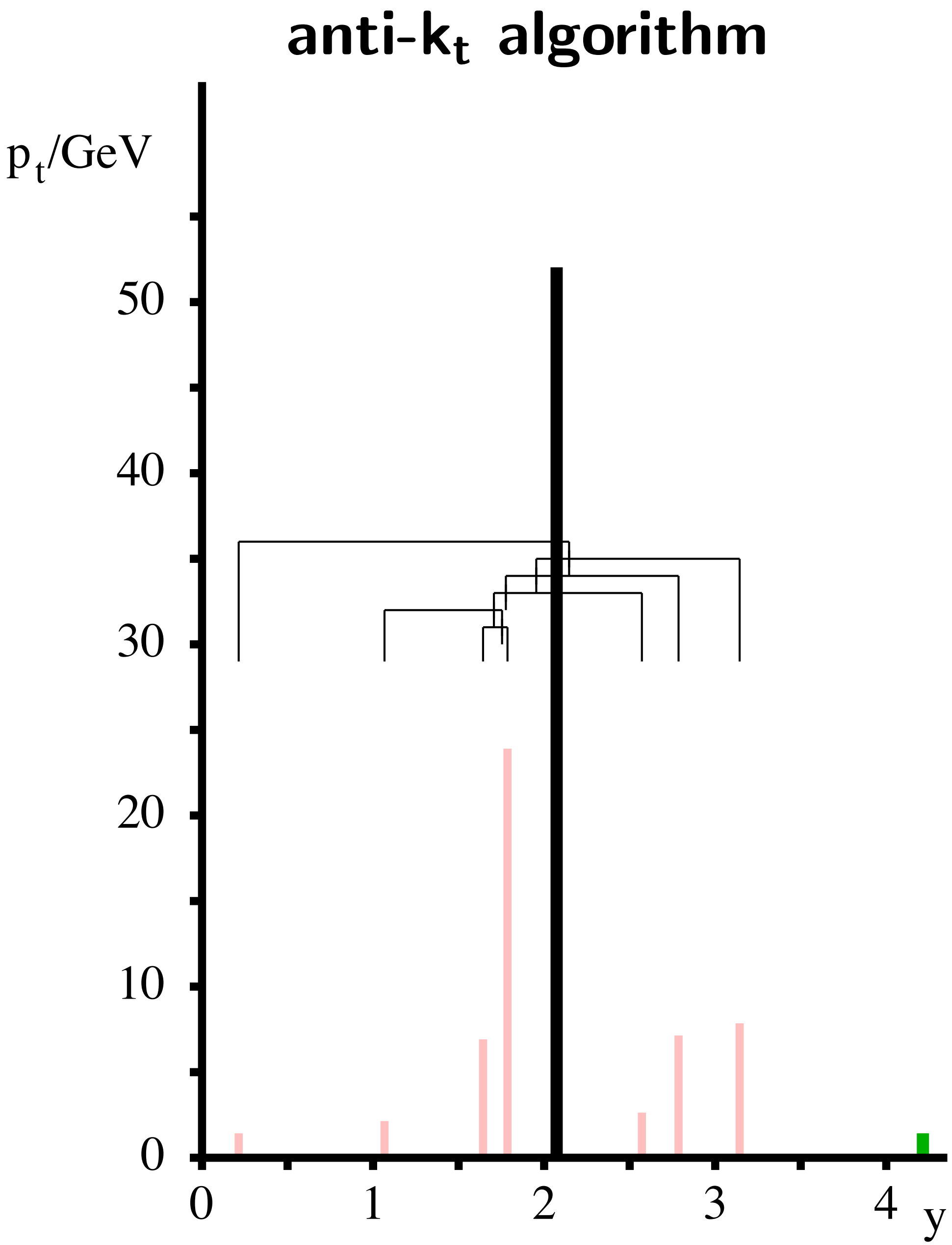

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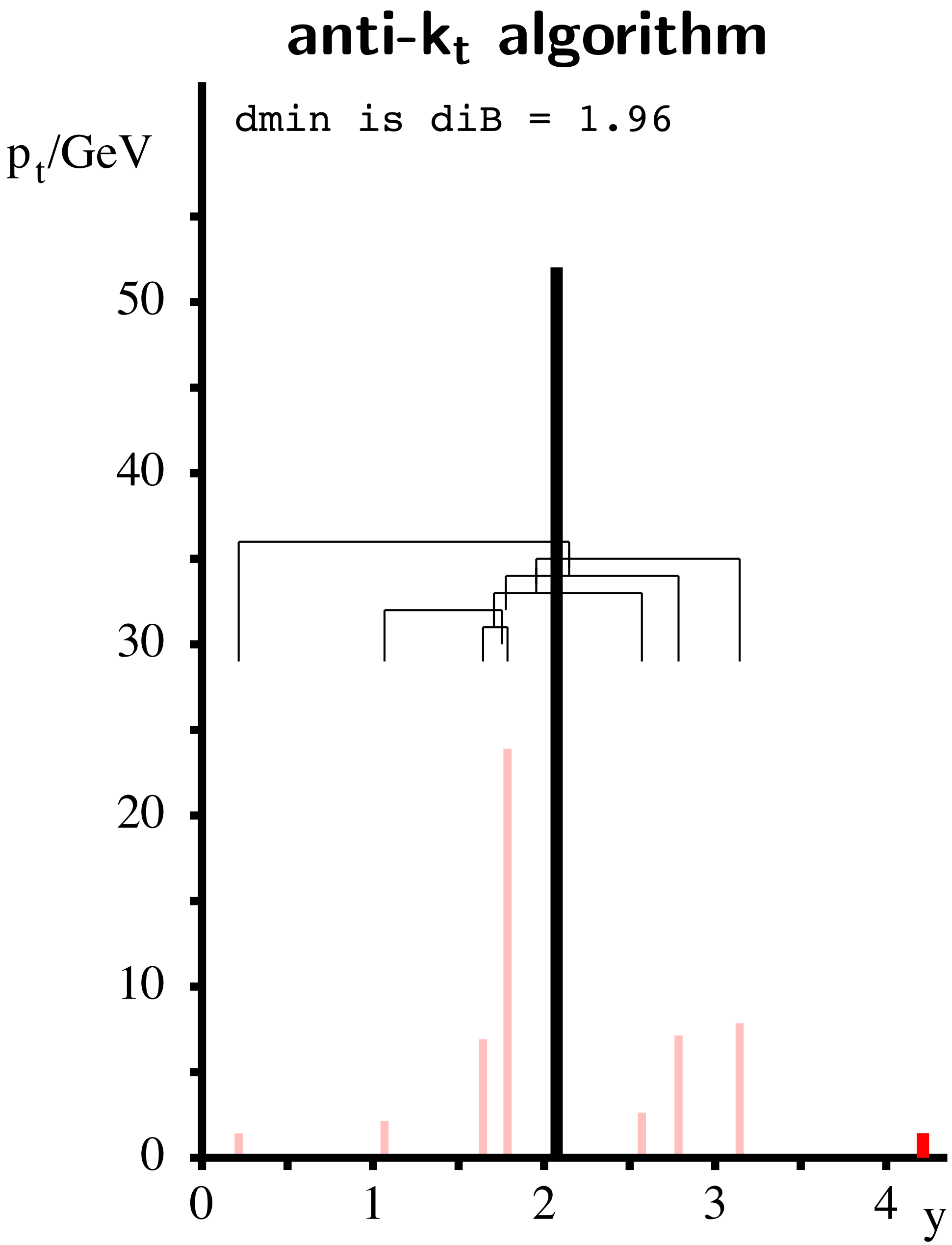

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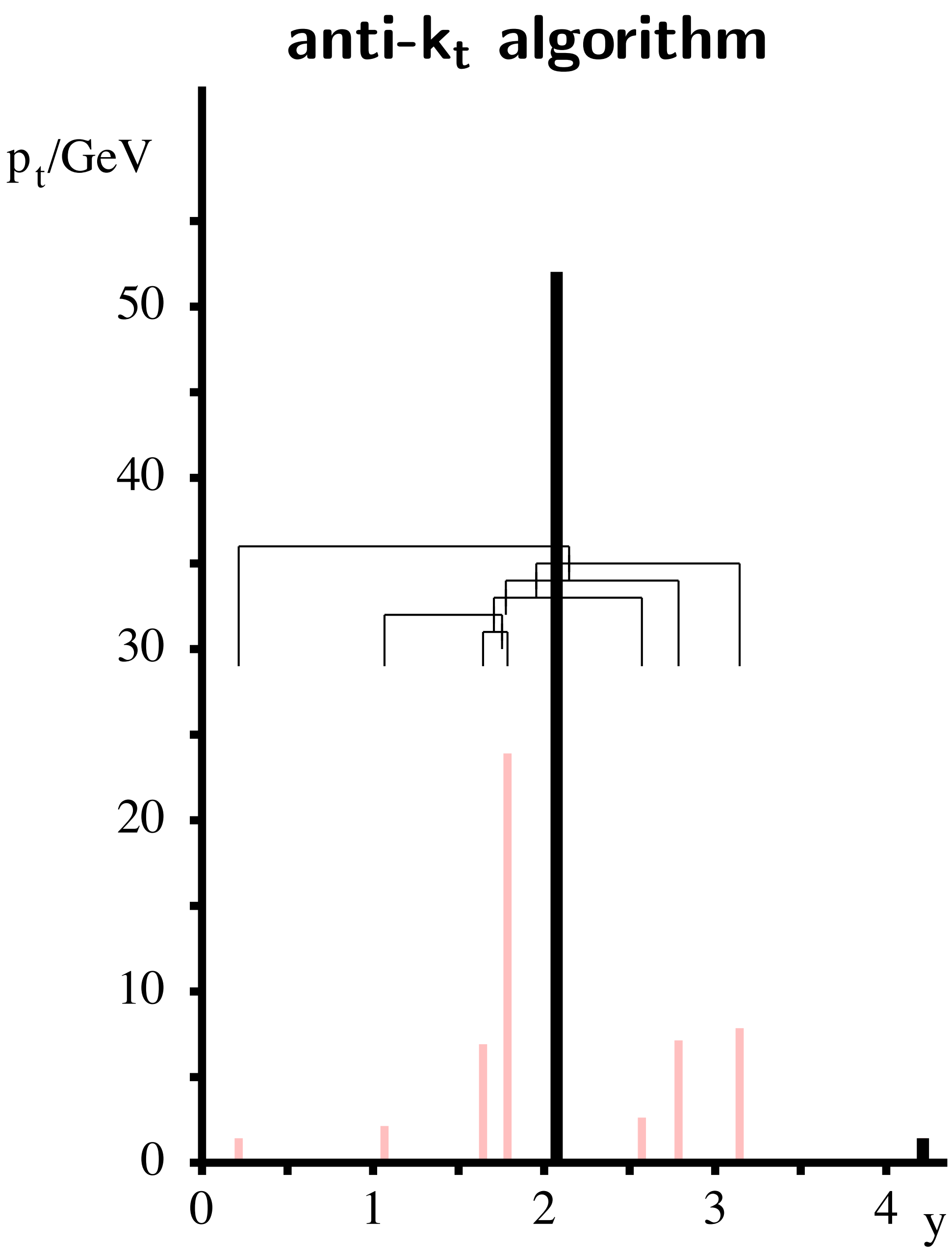

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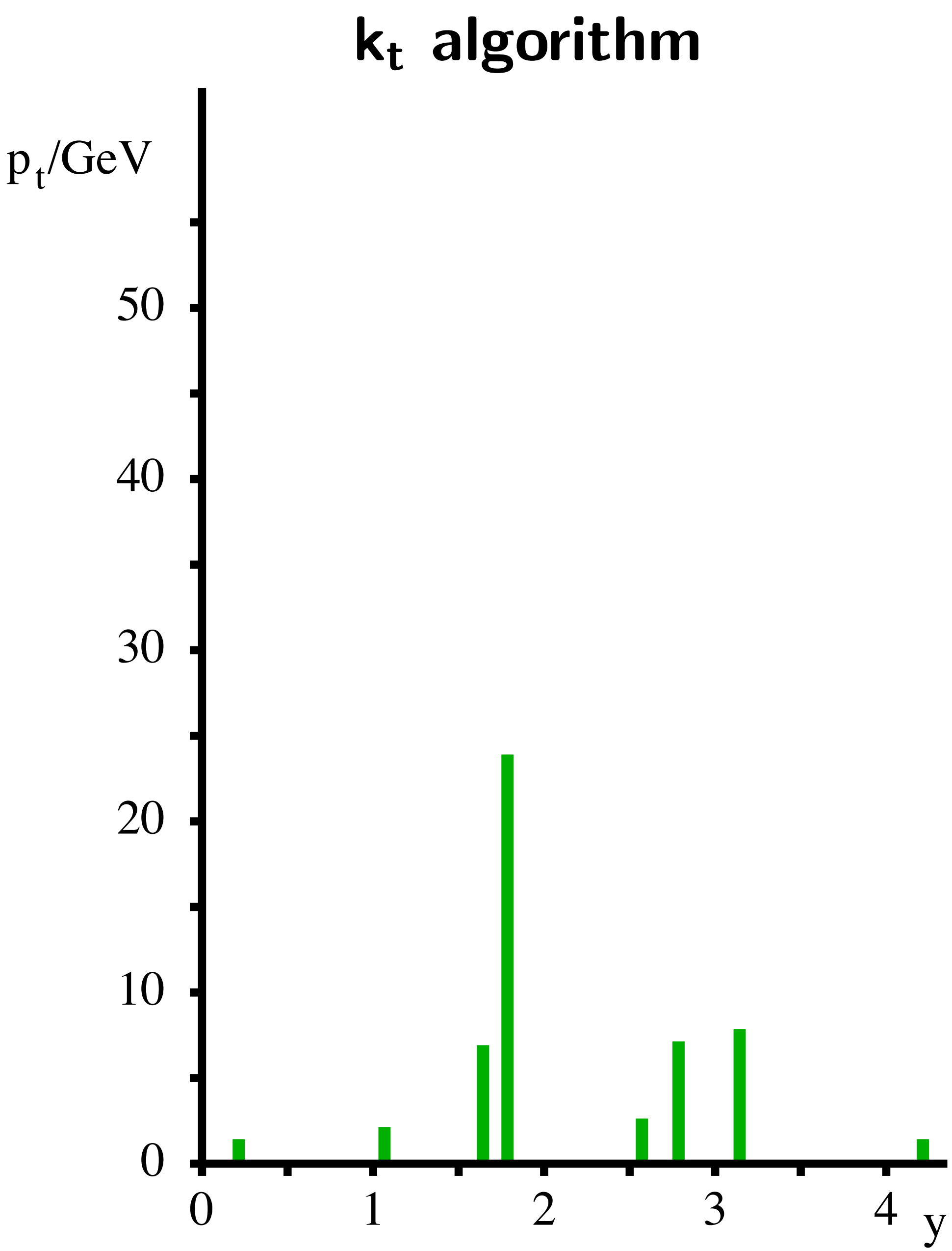
Second try

kt



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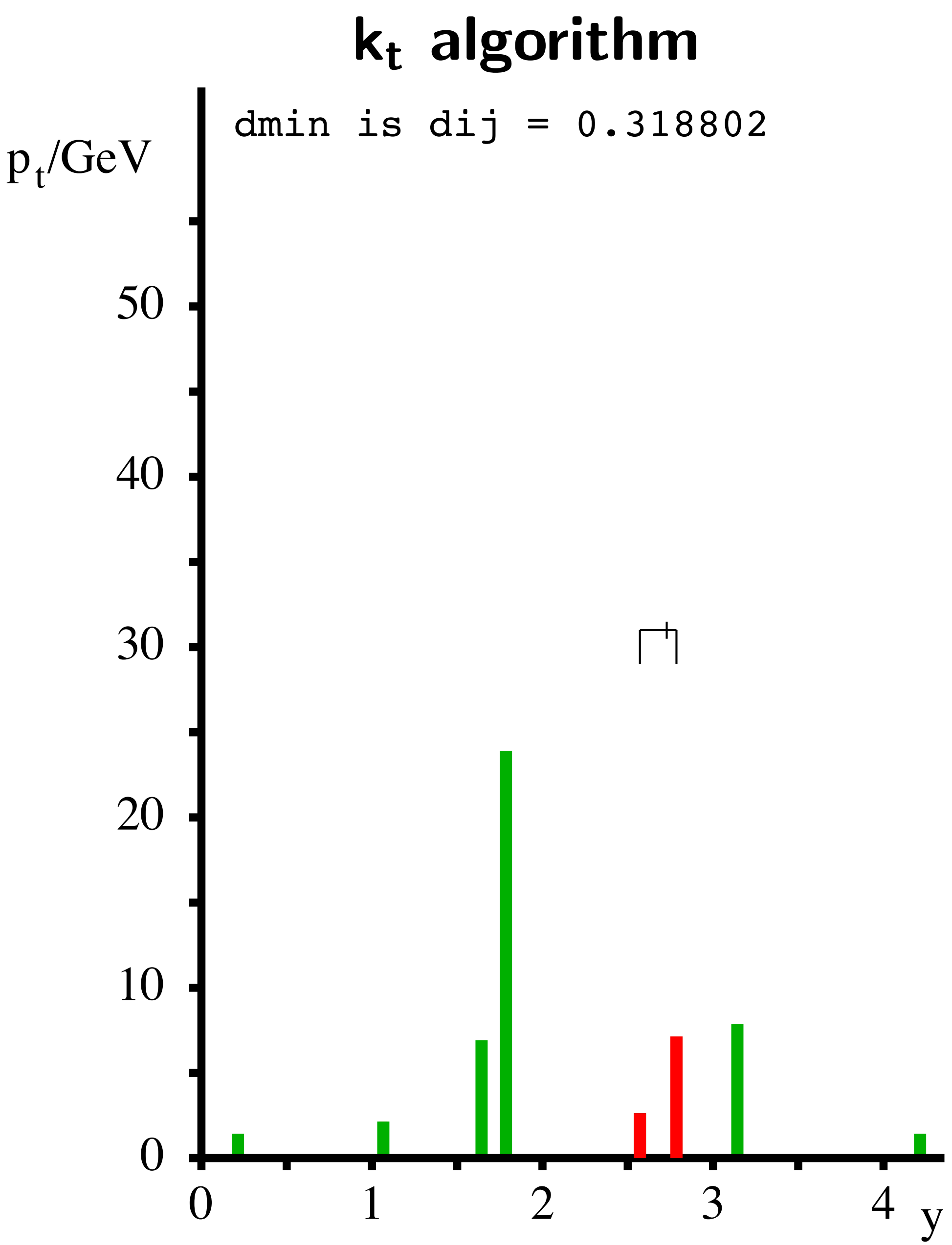

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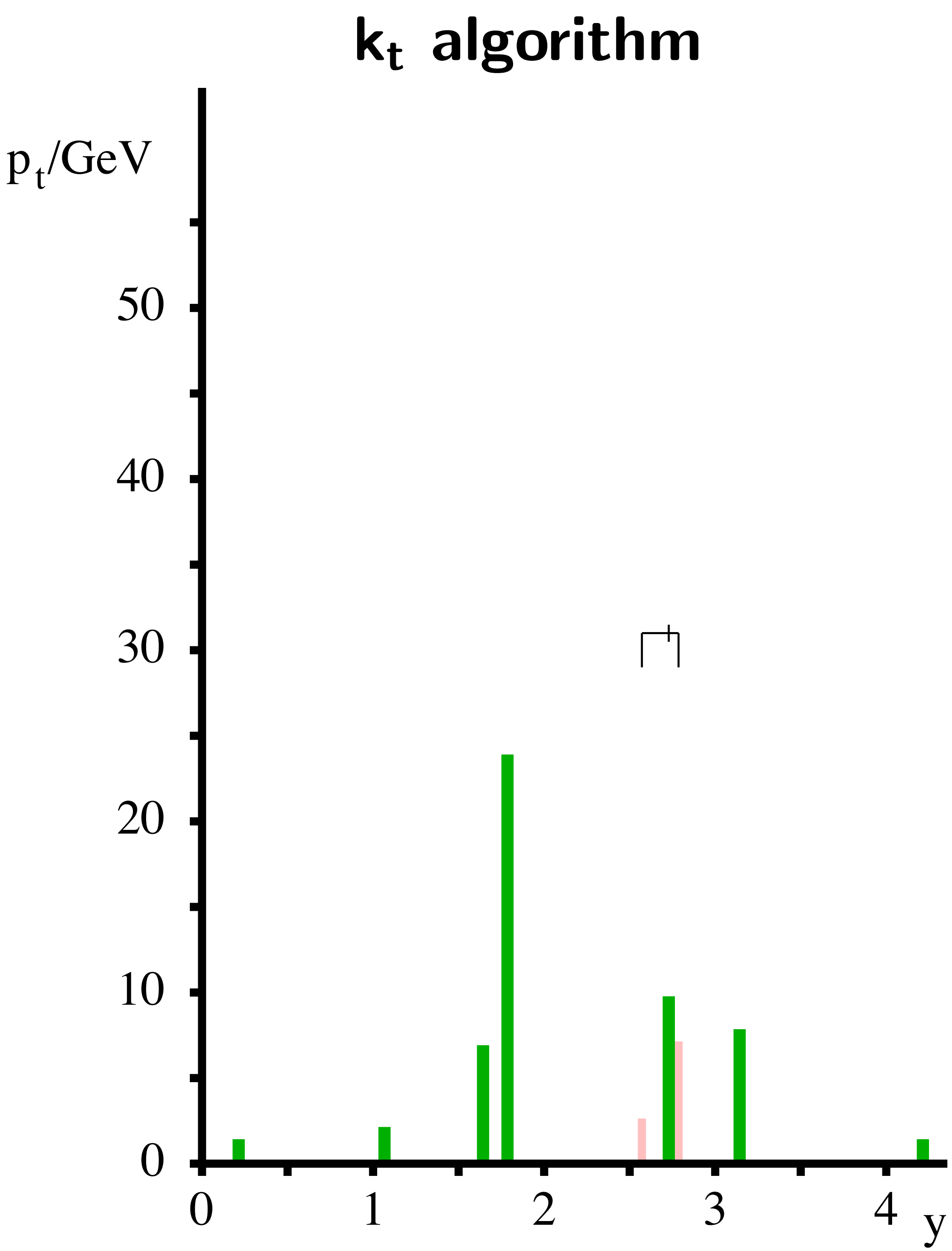

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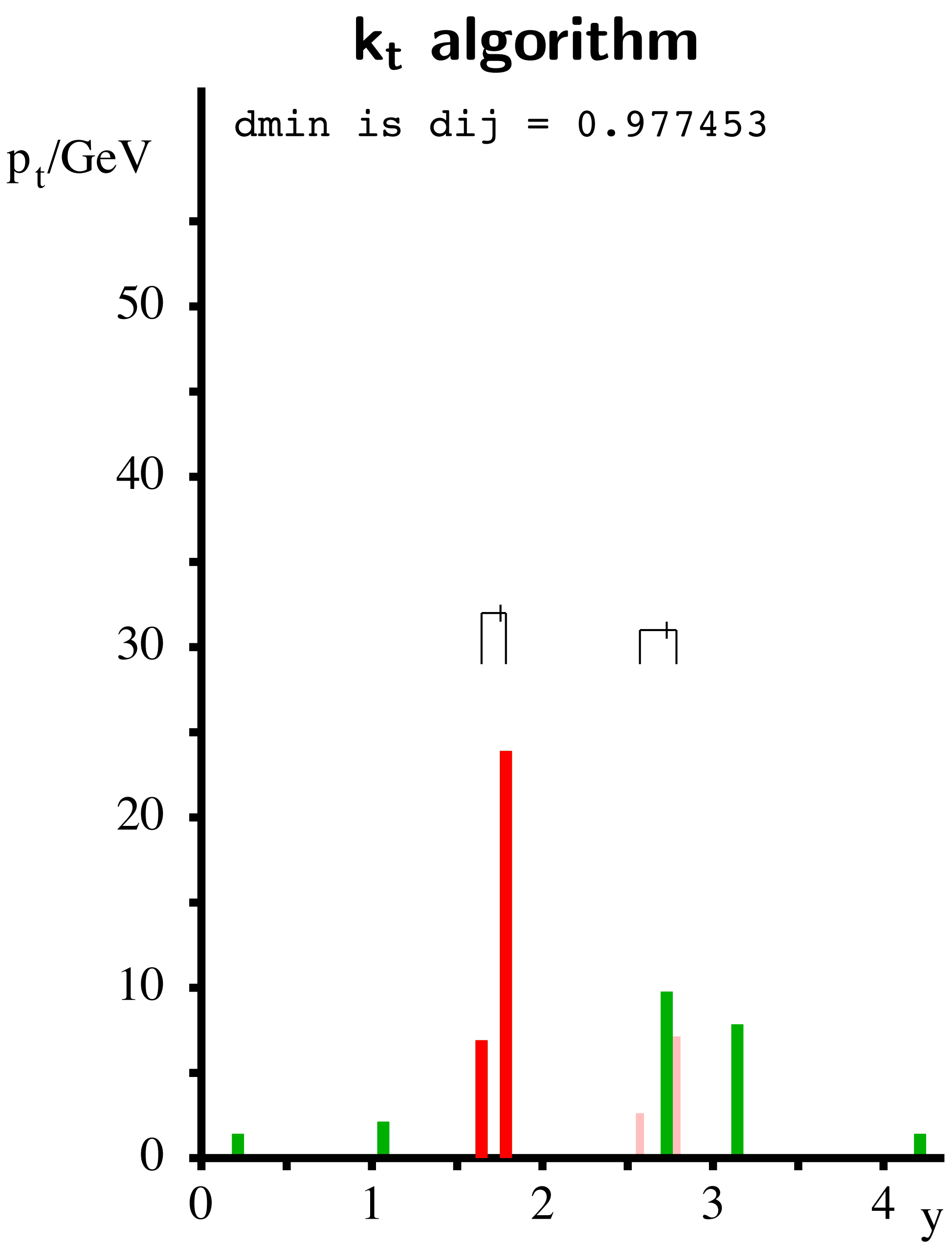

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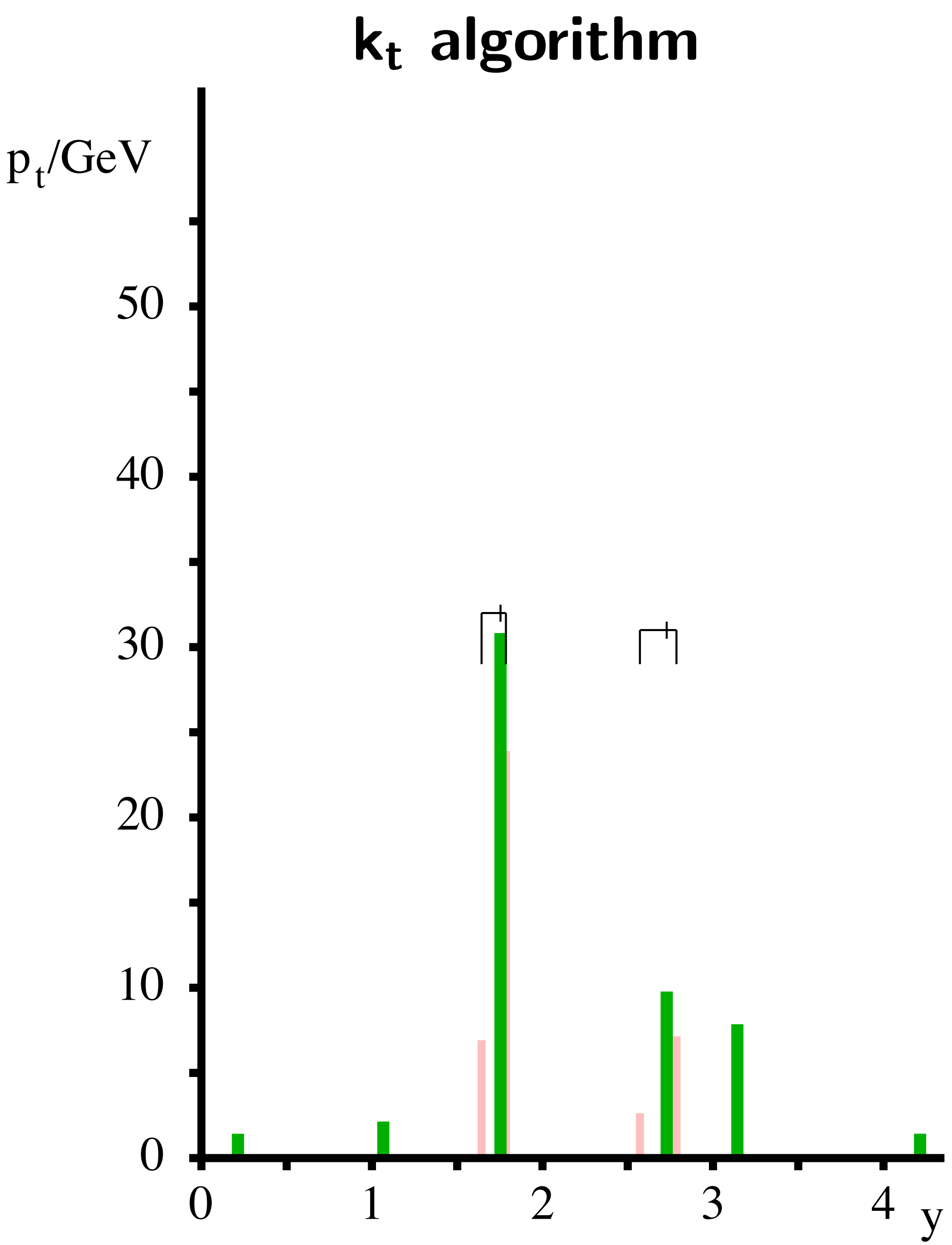

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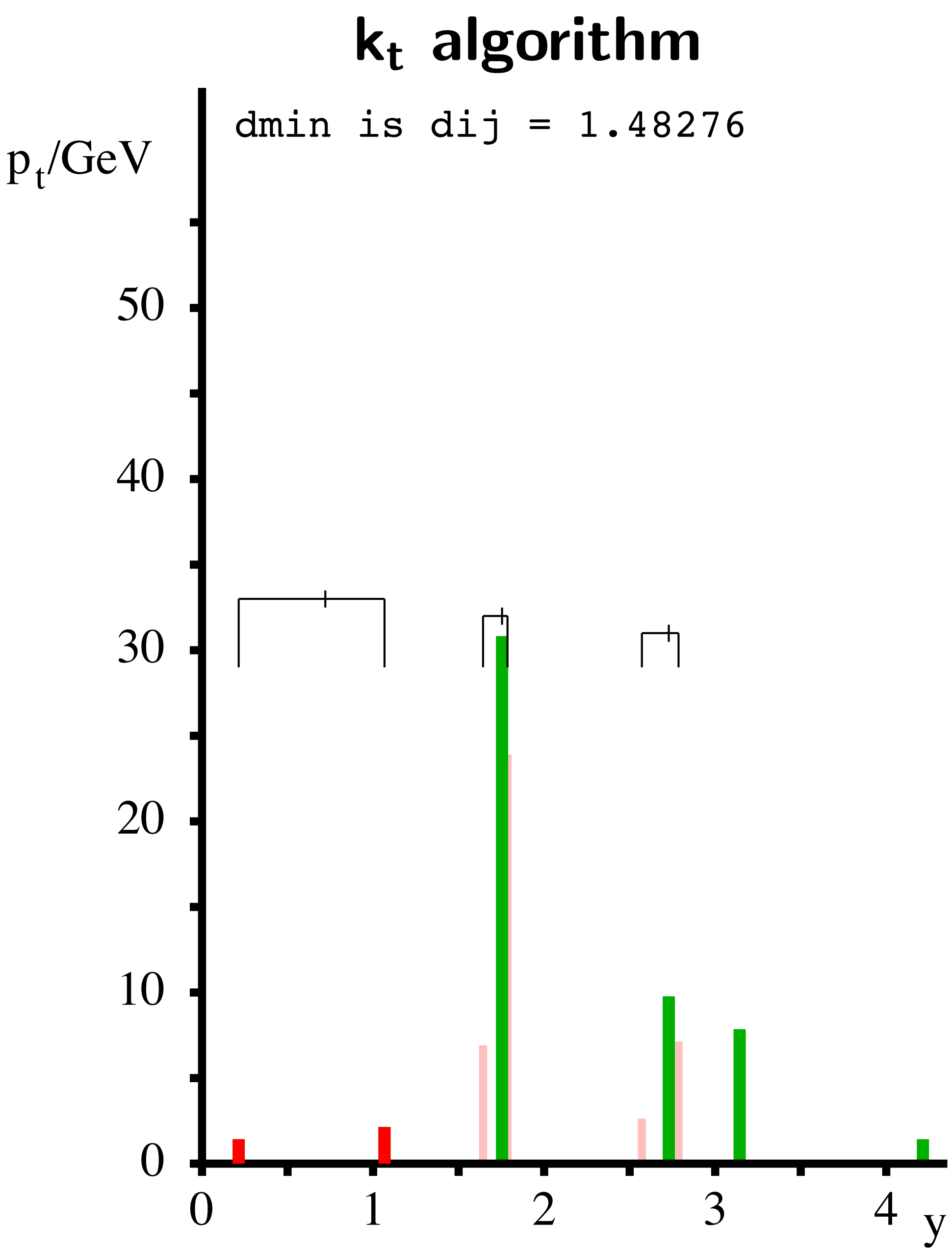

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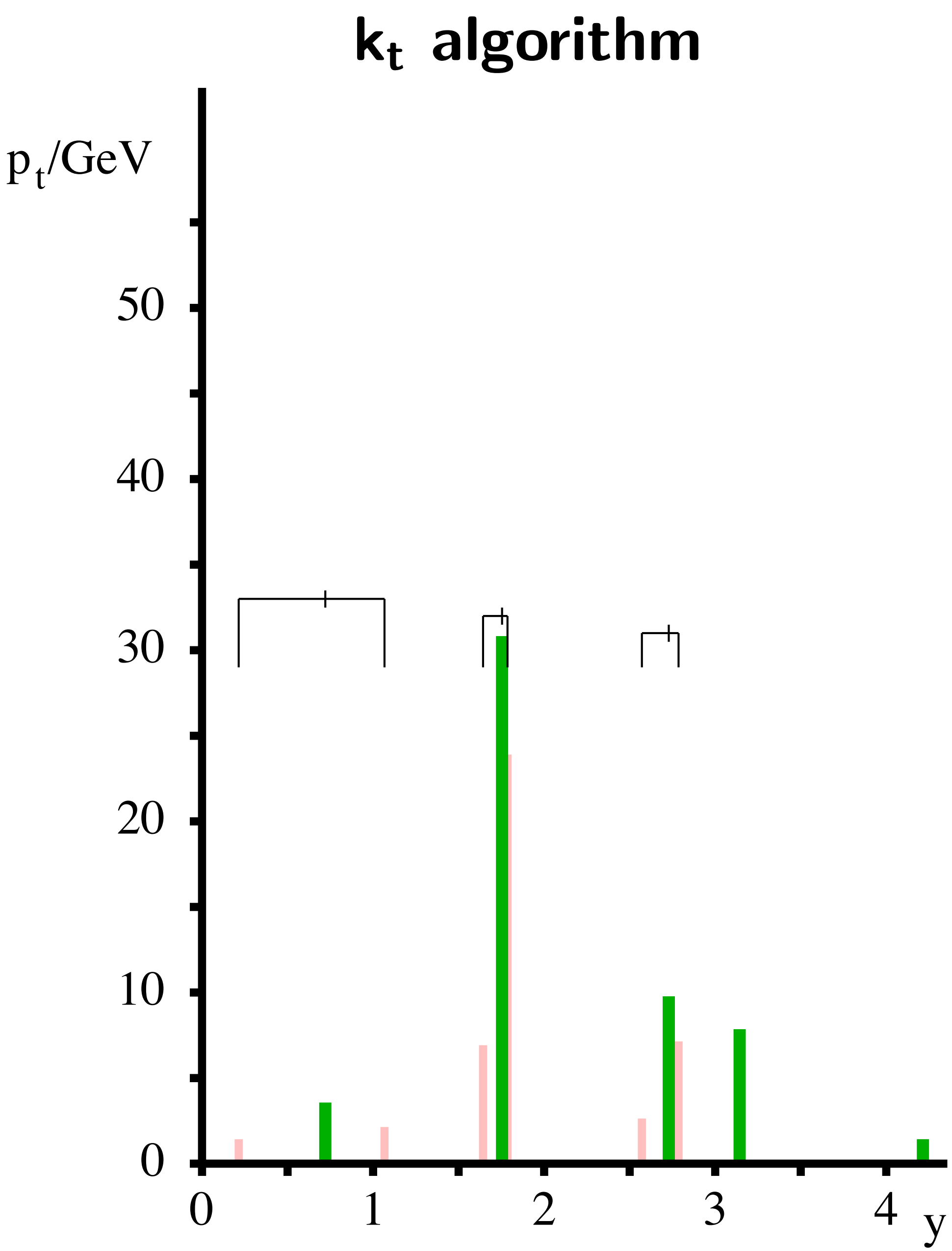

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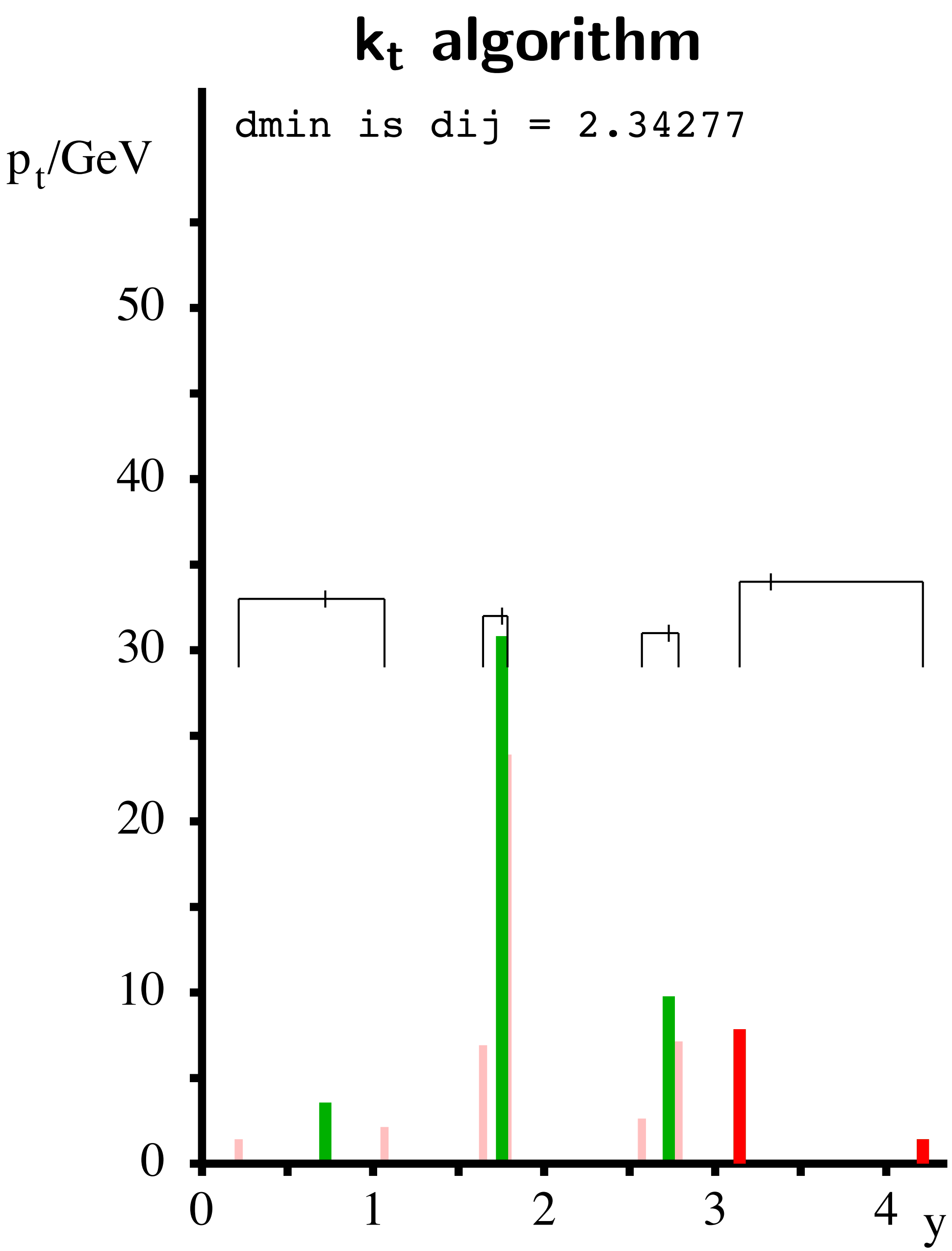

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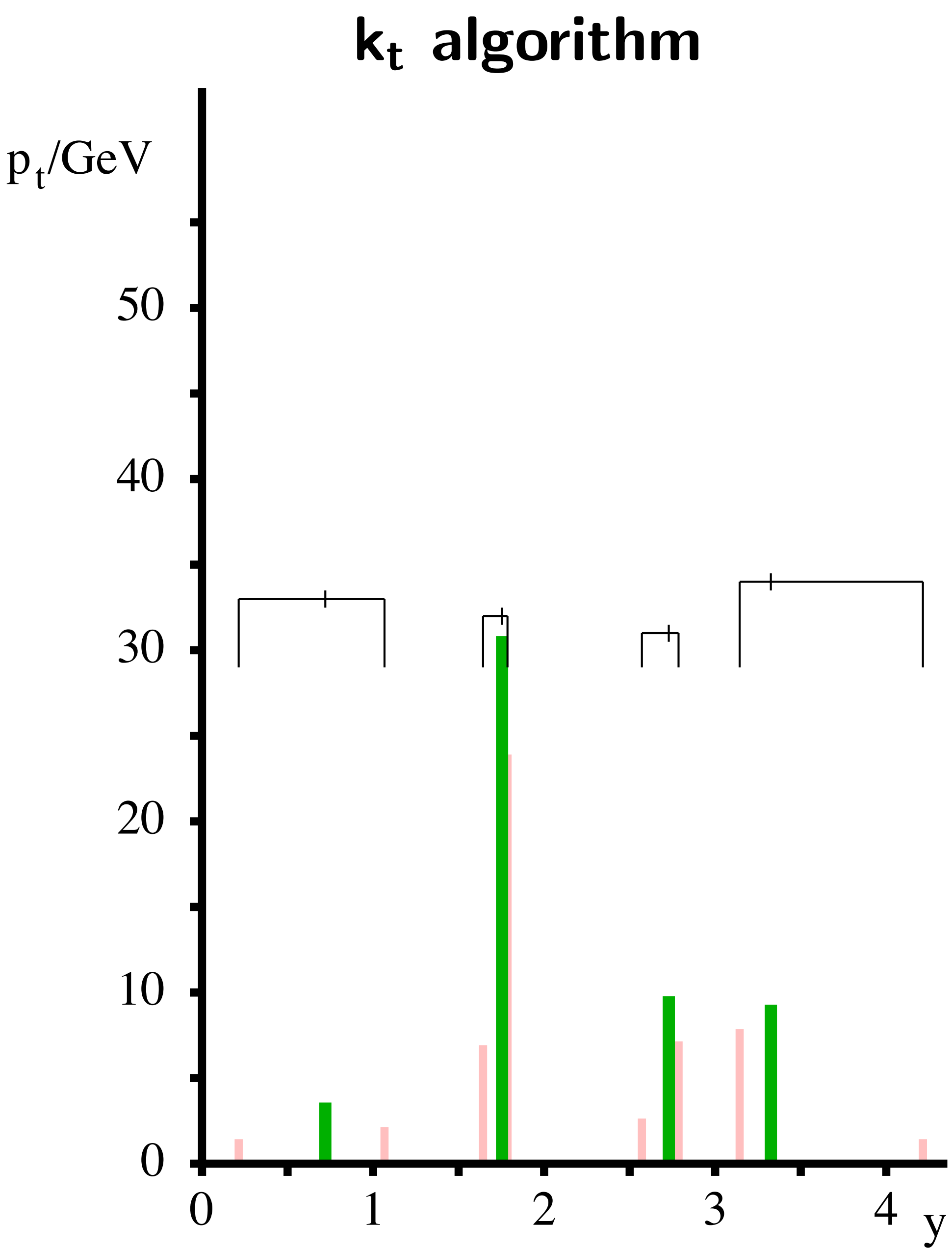

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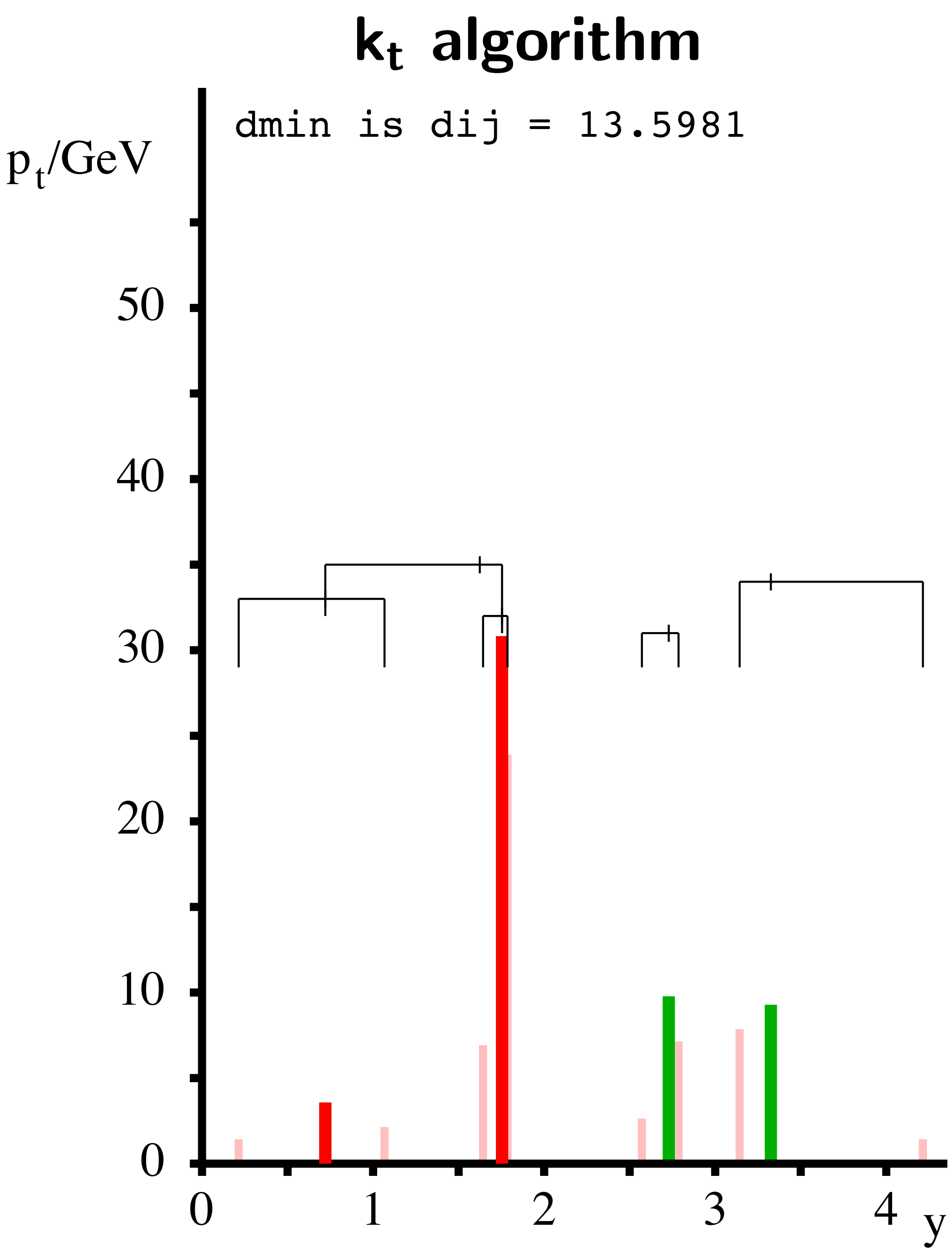

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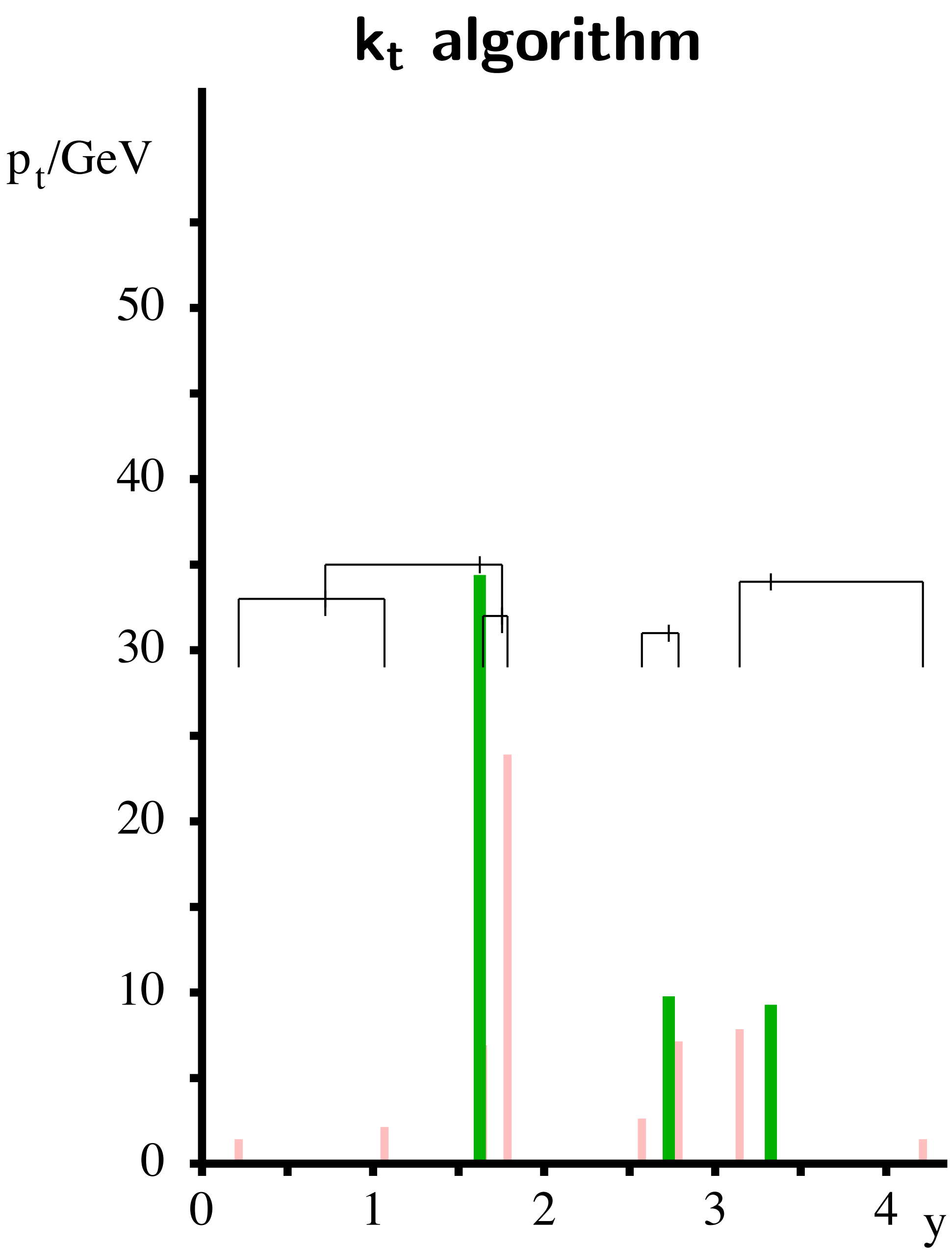

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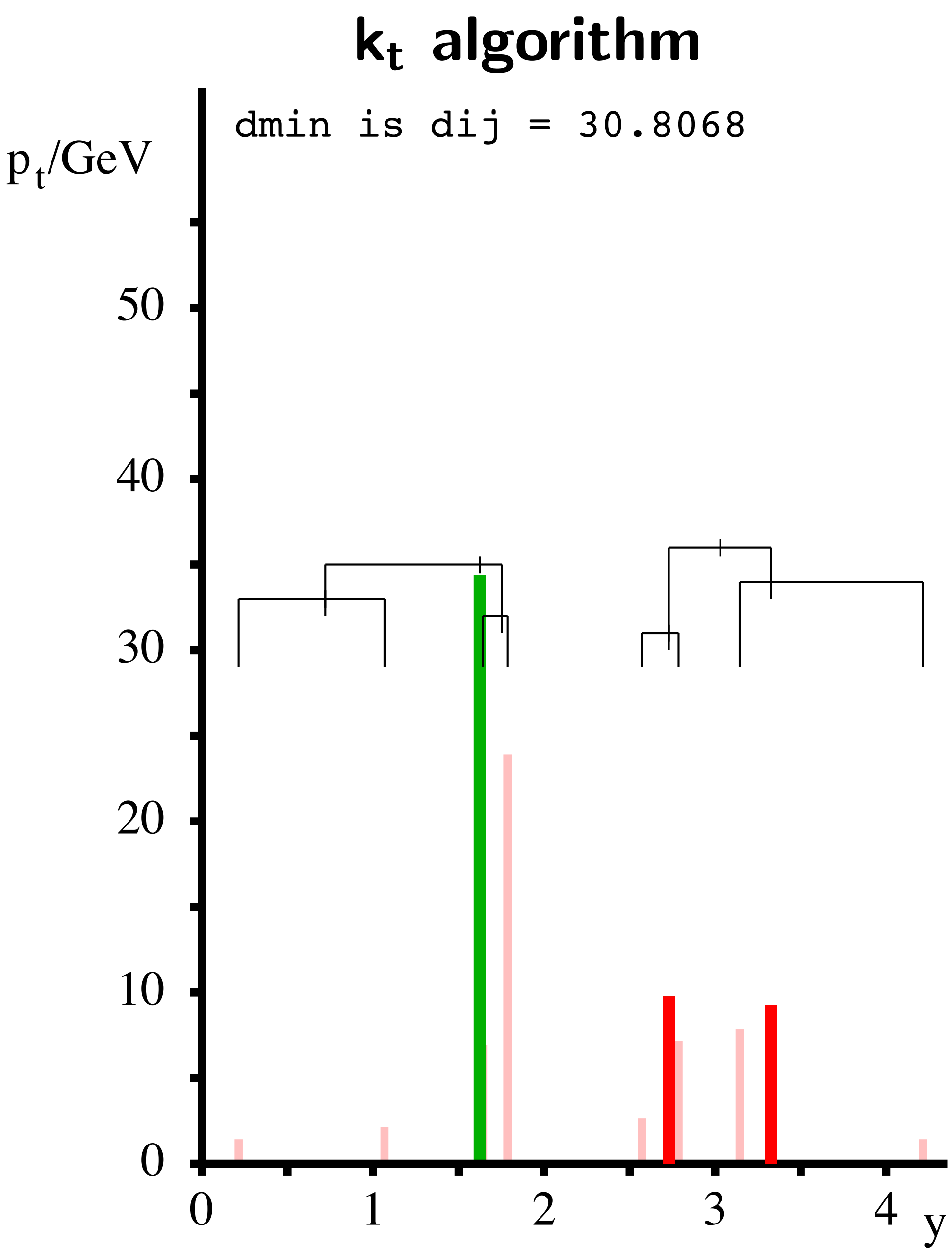

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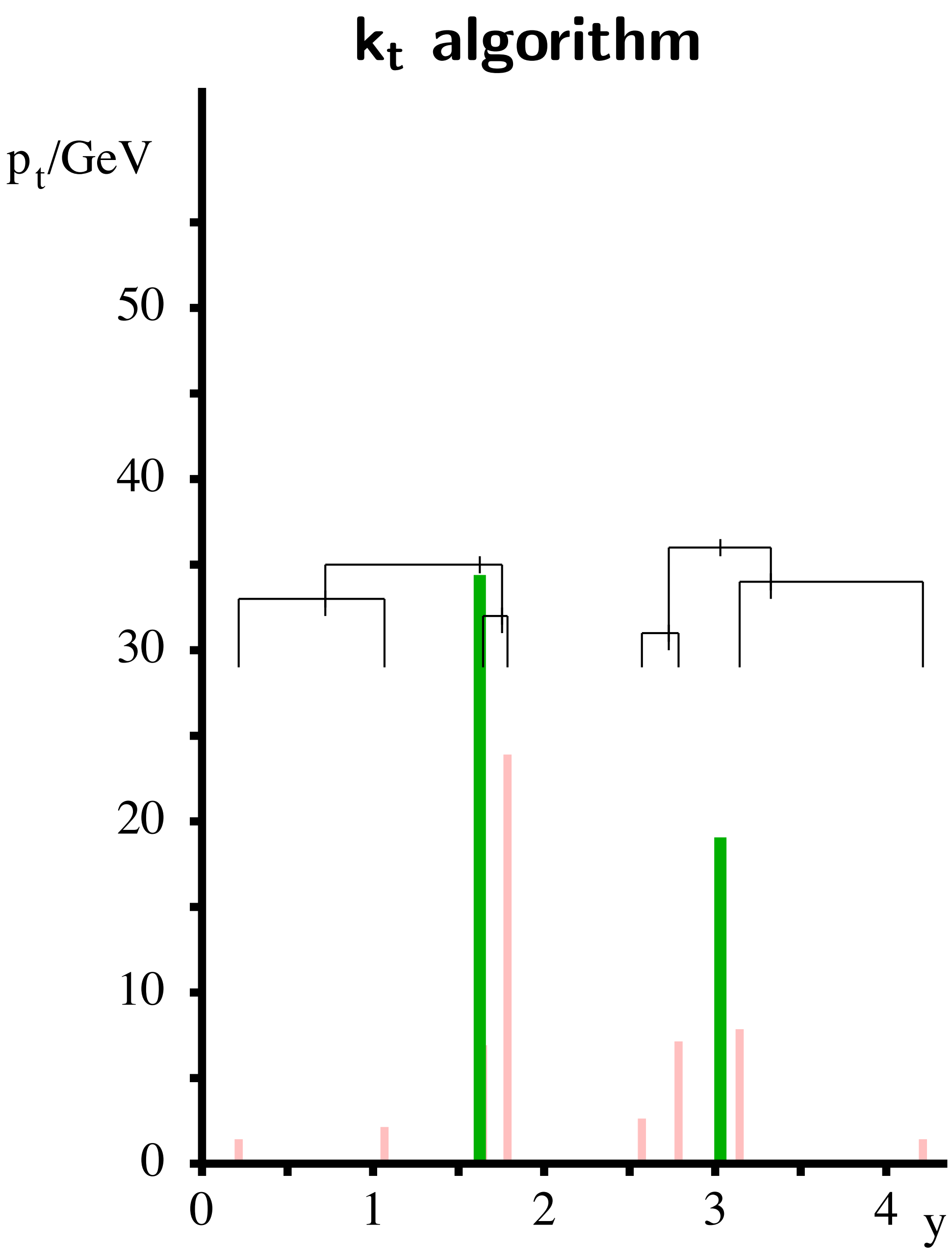

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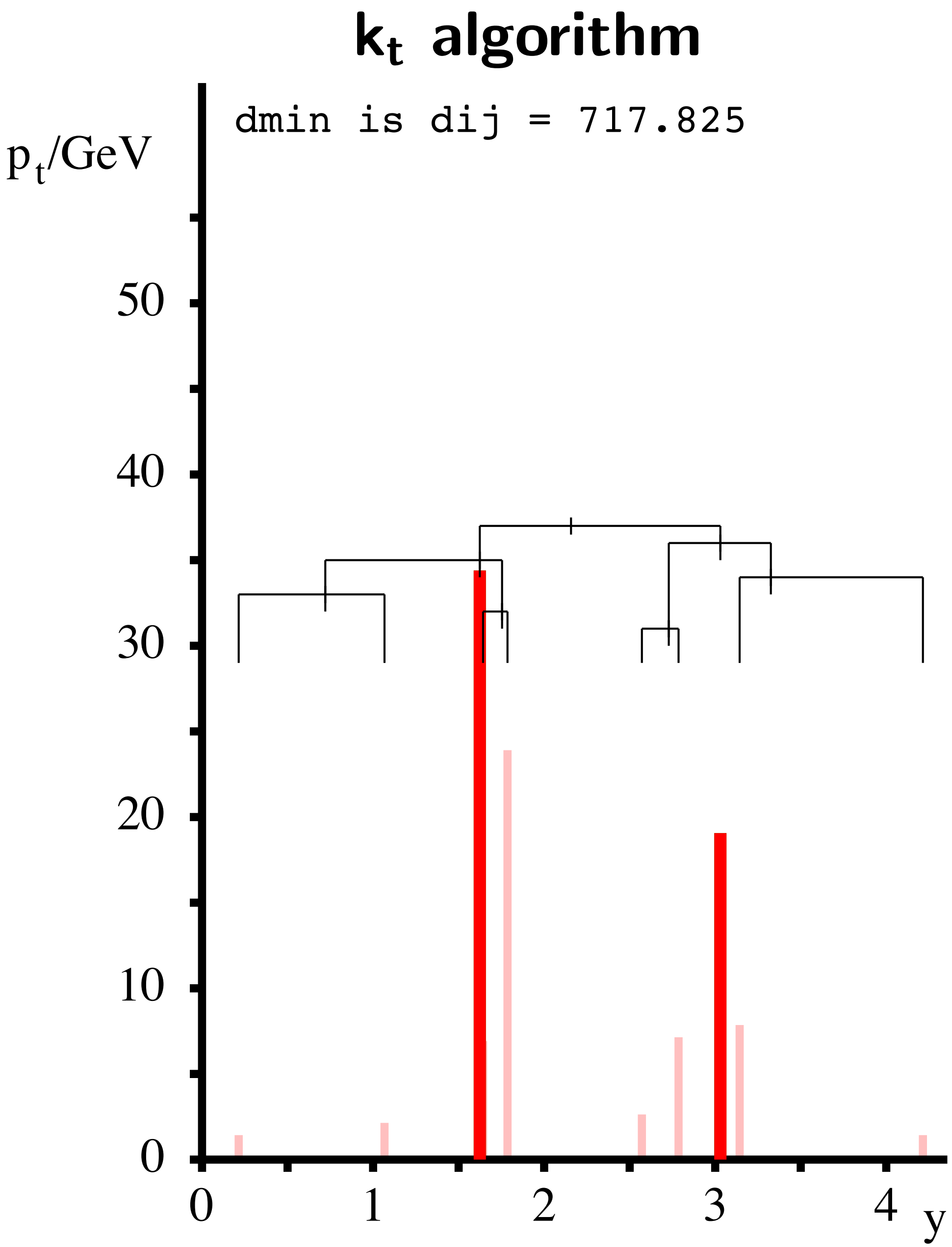

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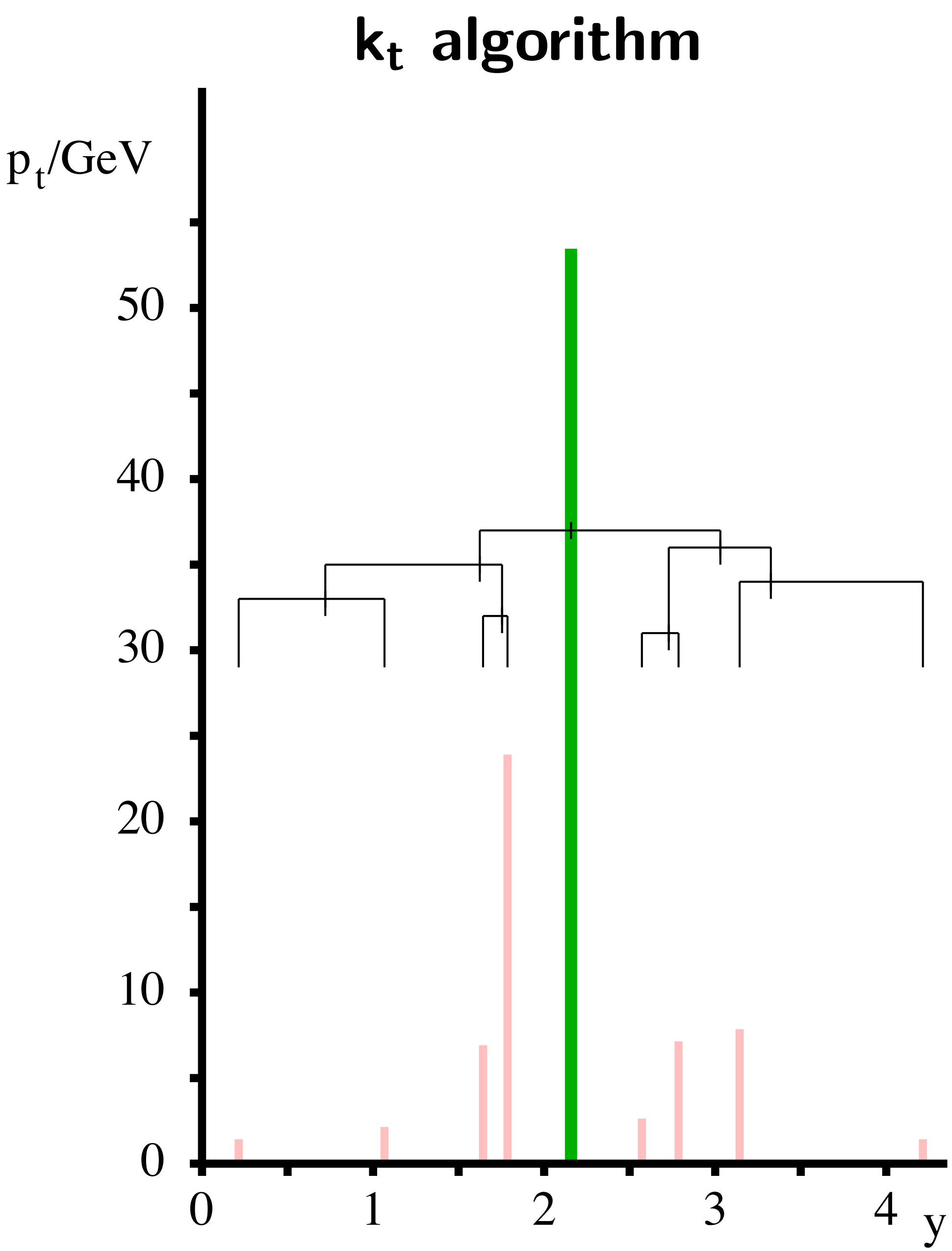

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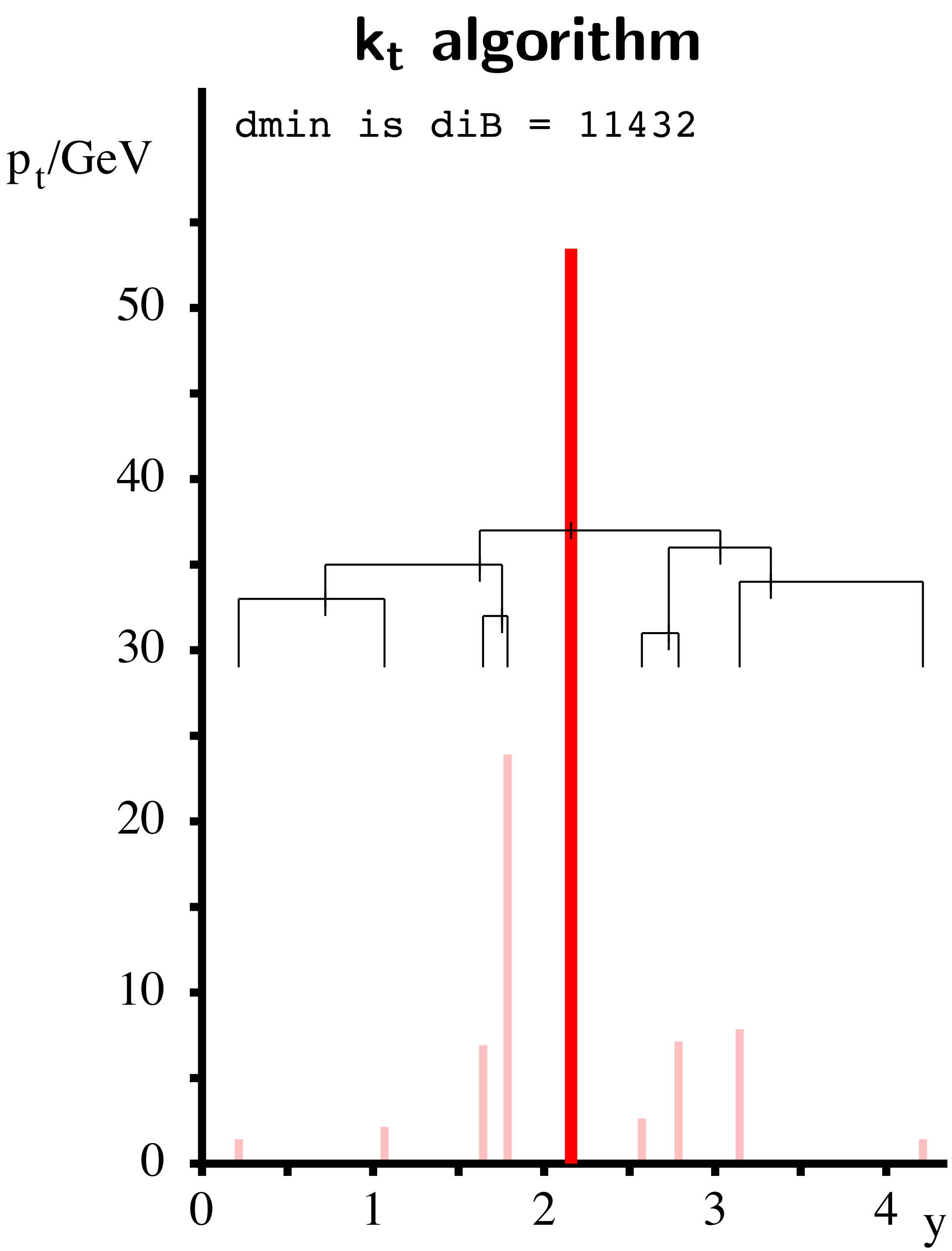

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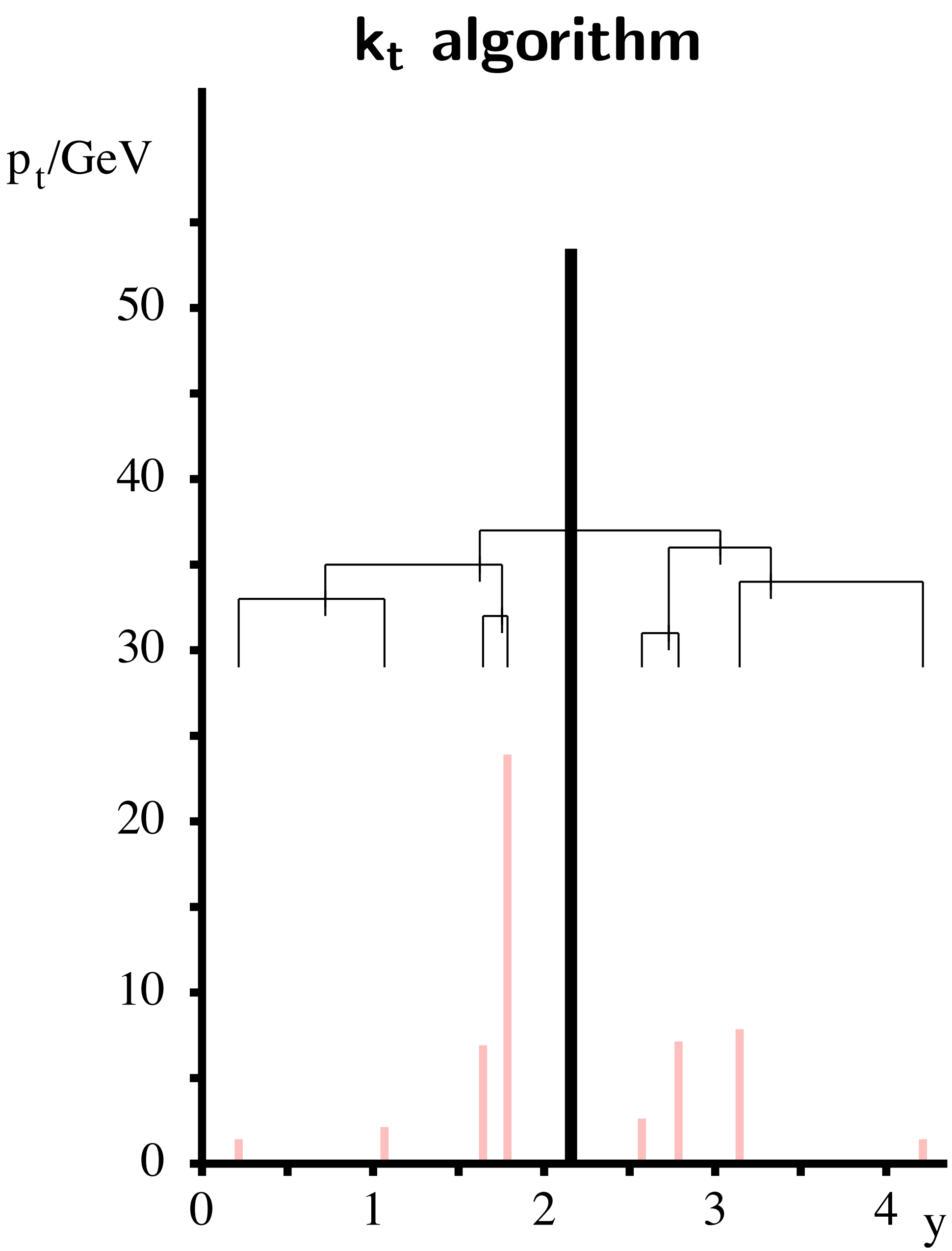

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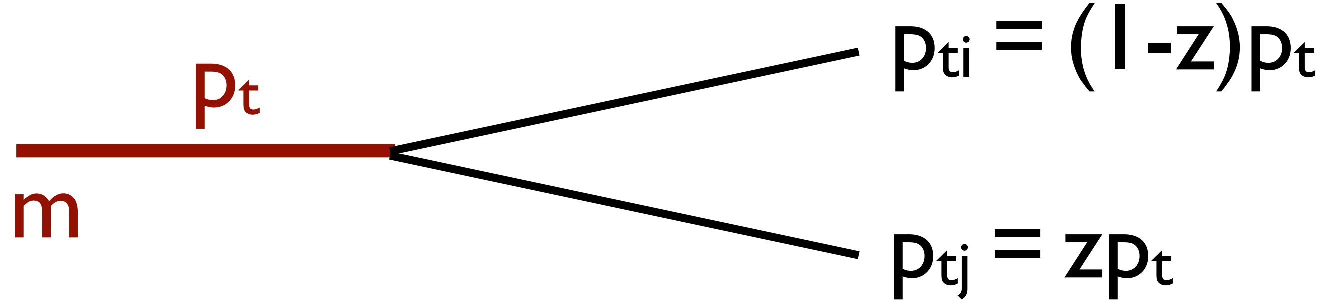
This meant it was the first algorithm to be used for jet substructure.

Seymour '93

Butterworth, Cox & Forshaw '02

Splittings and distances

Quasi-collinear splitting ($p_{tj} < p_{ti}$)



Invariant mass: $$m^2 \simeq p_{ti}p_{tj}\Delta R_{ij}^2 = (1-z)zp_t^2\Delta R_{ij}^2$$

k_t distance: $$d_{ij} \overset{(p_{tj} < p_{ti})}{=} z^2 p_t^2 \Delta R_{ij}^2 \simeq \frac{z}{1-z} m^2$$

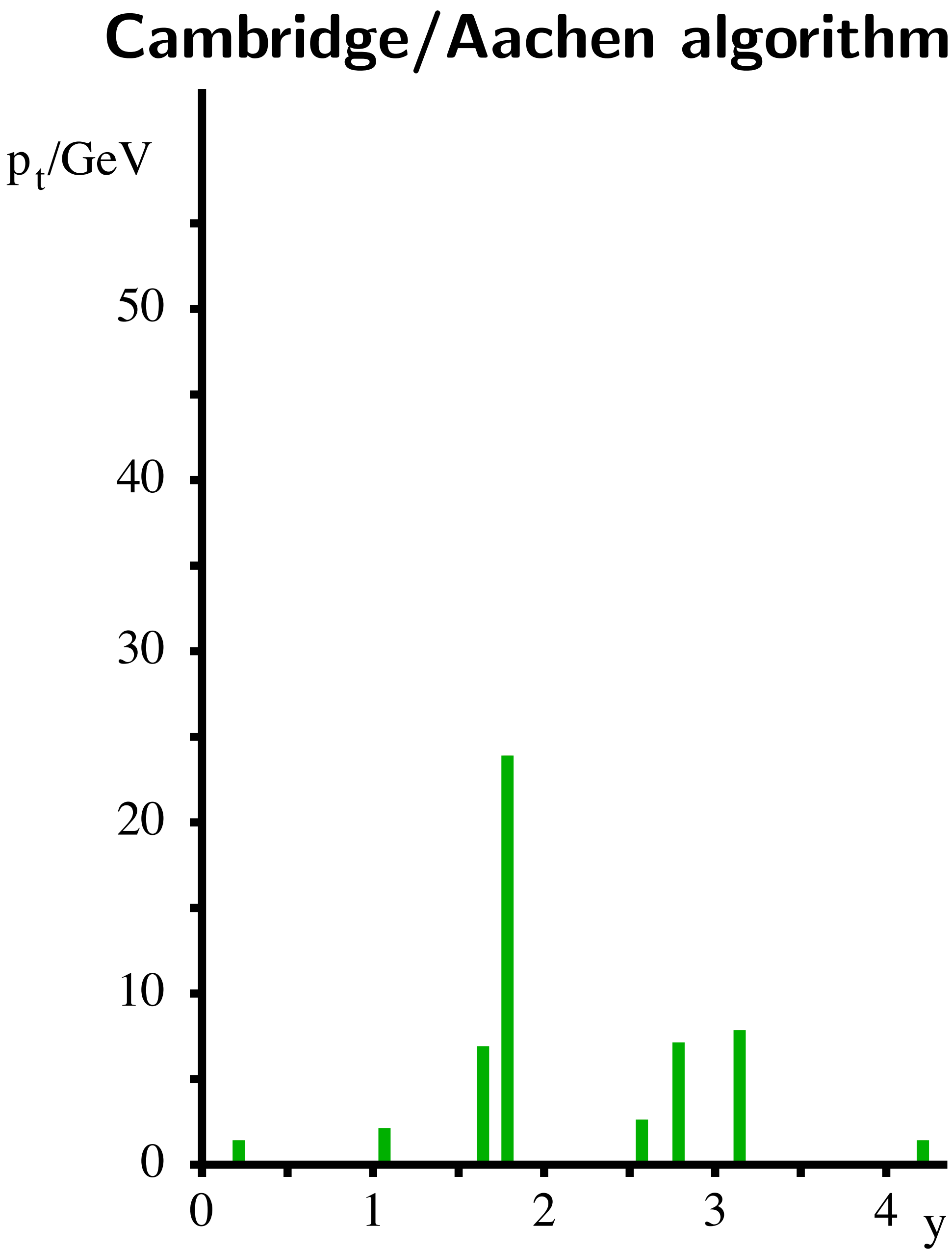
For a given mass, the **background** (parton shower) will have smaller distance d_{ij} than the **signal** (symmetric 1→2 decay), i.e. it will tend to **cluster earlier** in the k_t algorithm

Potential tagger: last clustering in k_t algorithm

This is where the hierarchy of the k_t algorithm becomes relevant. QCD radiation is clustered first, and only at the end the symmetric, large-angle splittings due to decays are reclustered

Third try

Cambridge/Aachen



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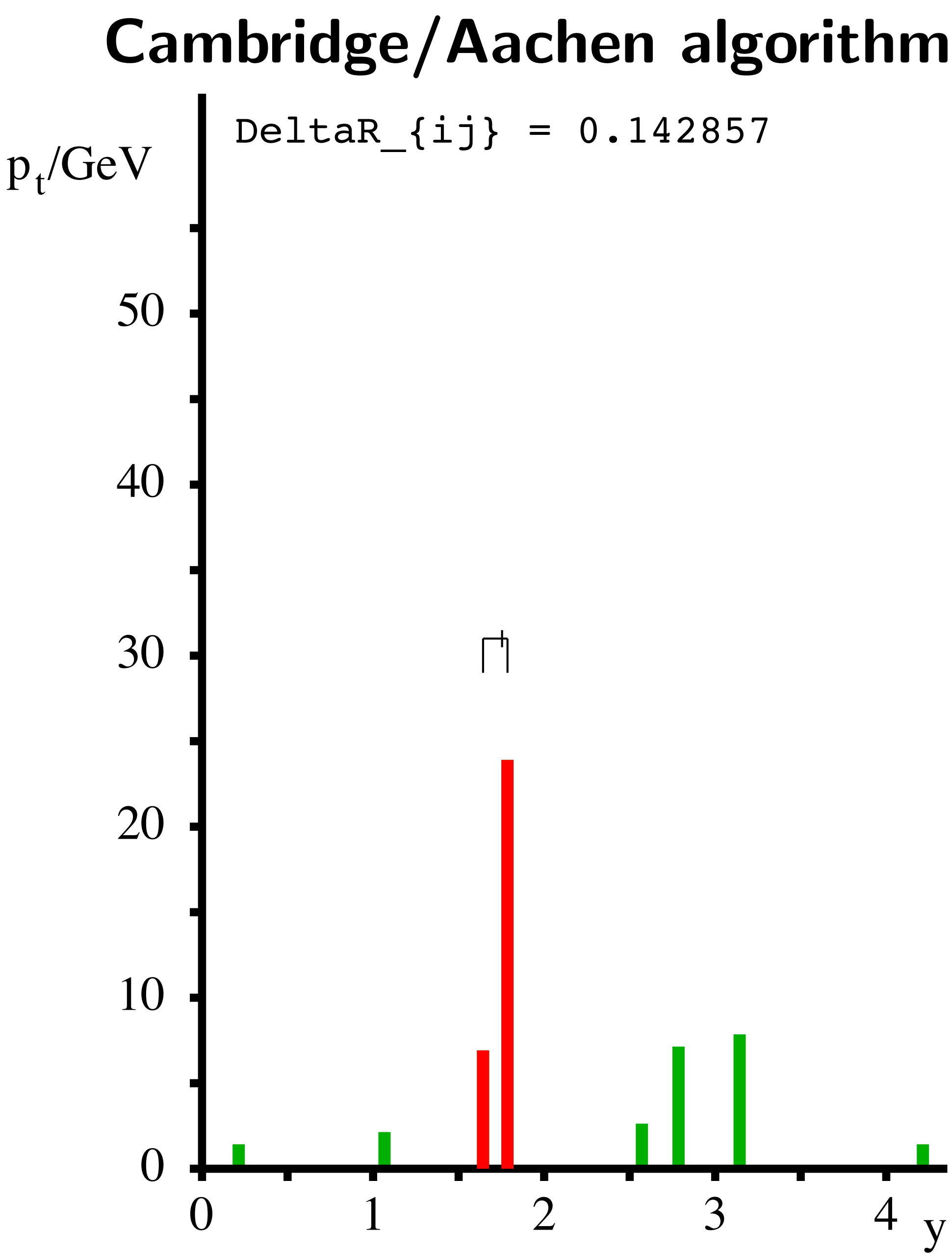

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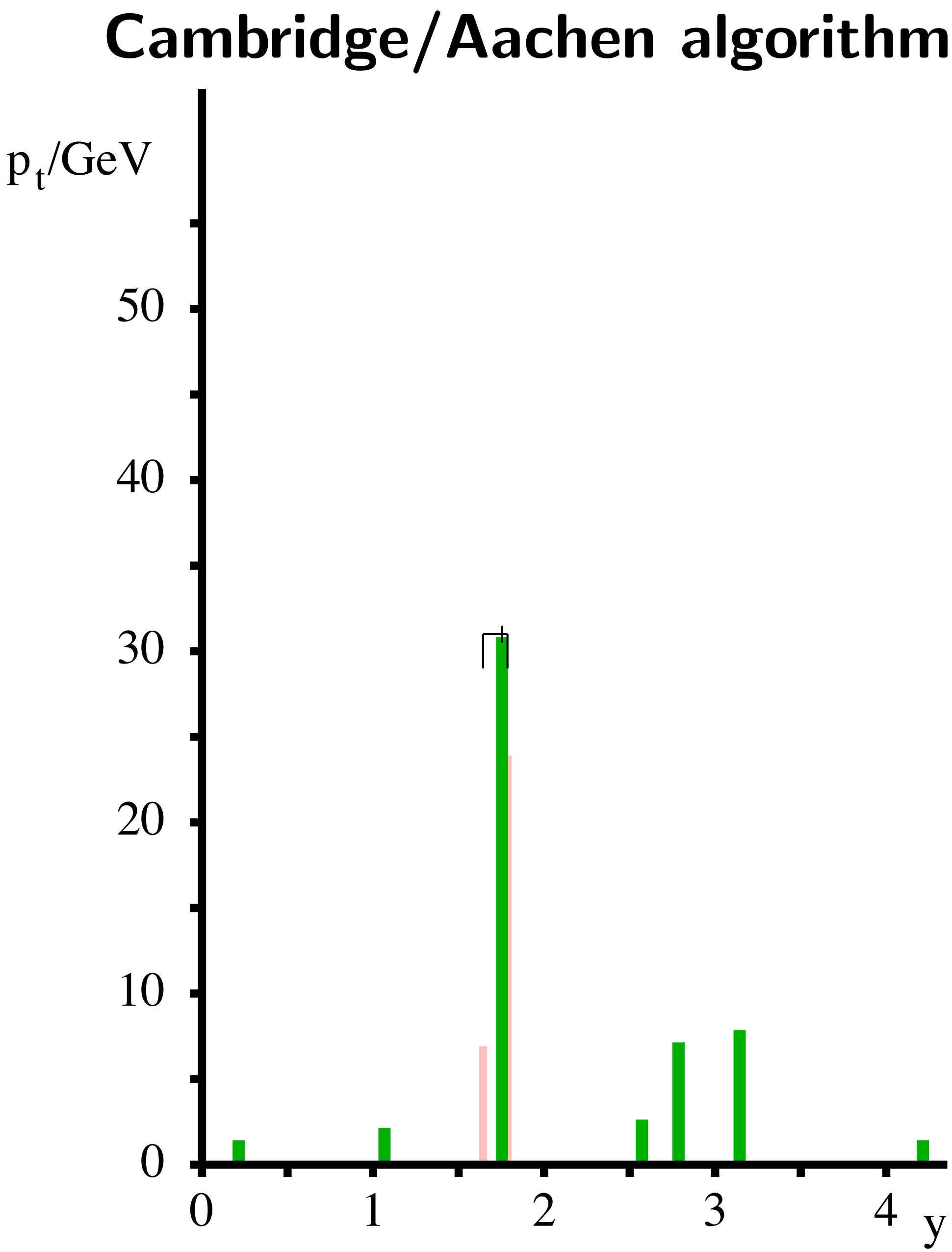

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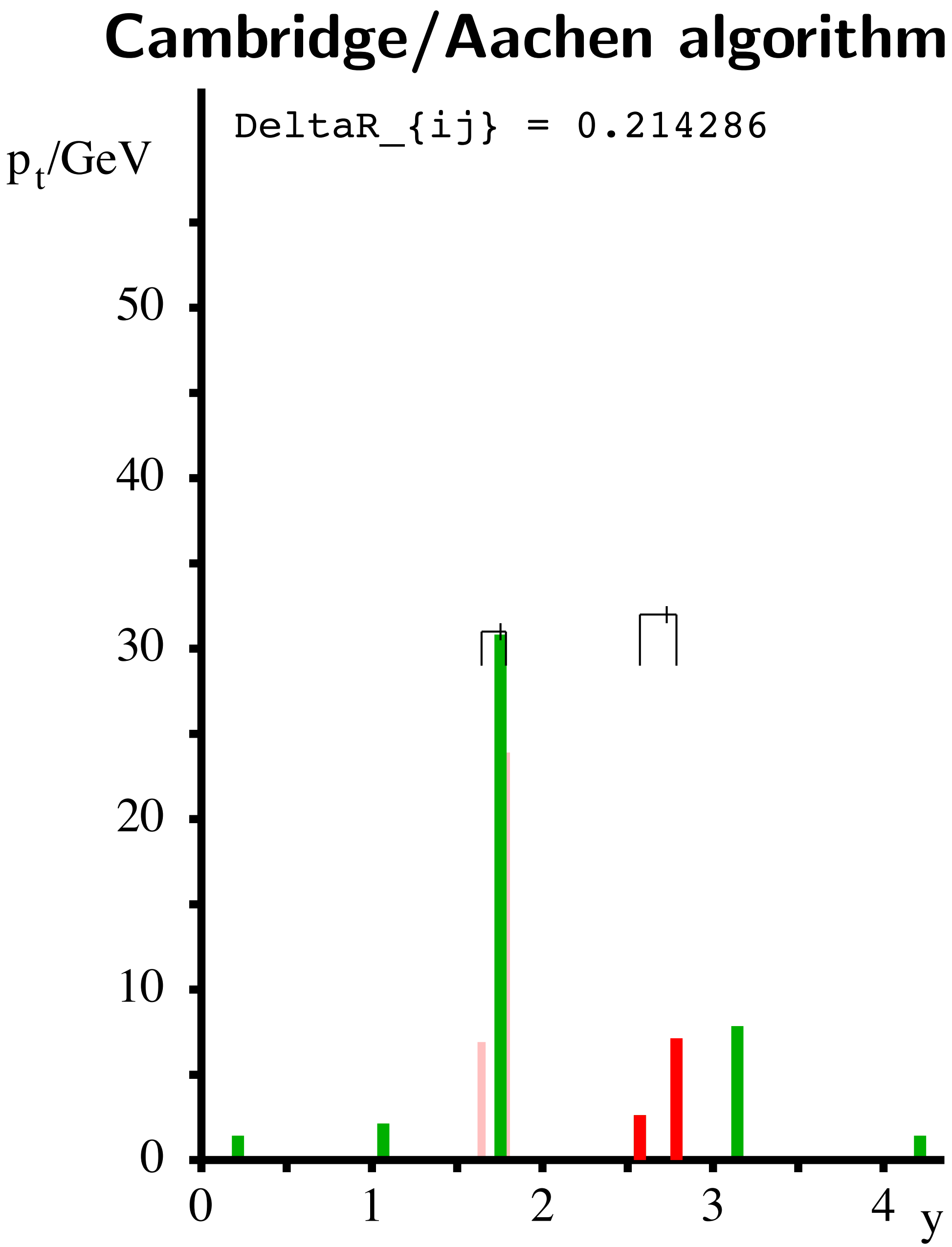

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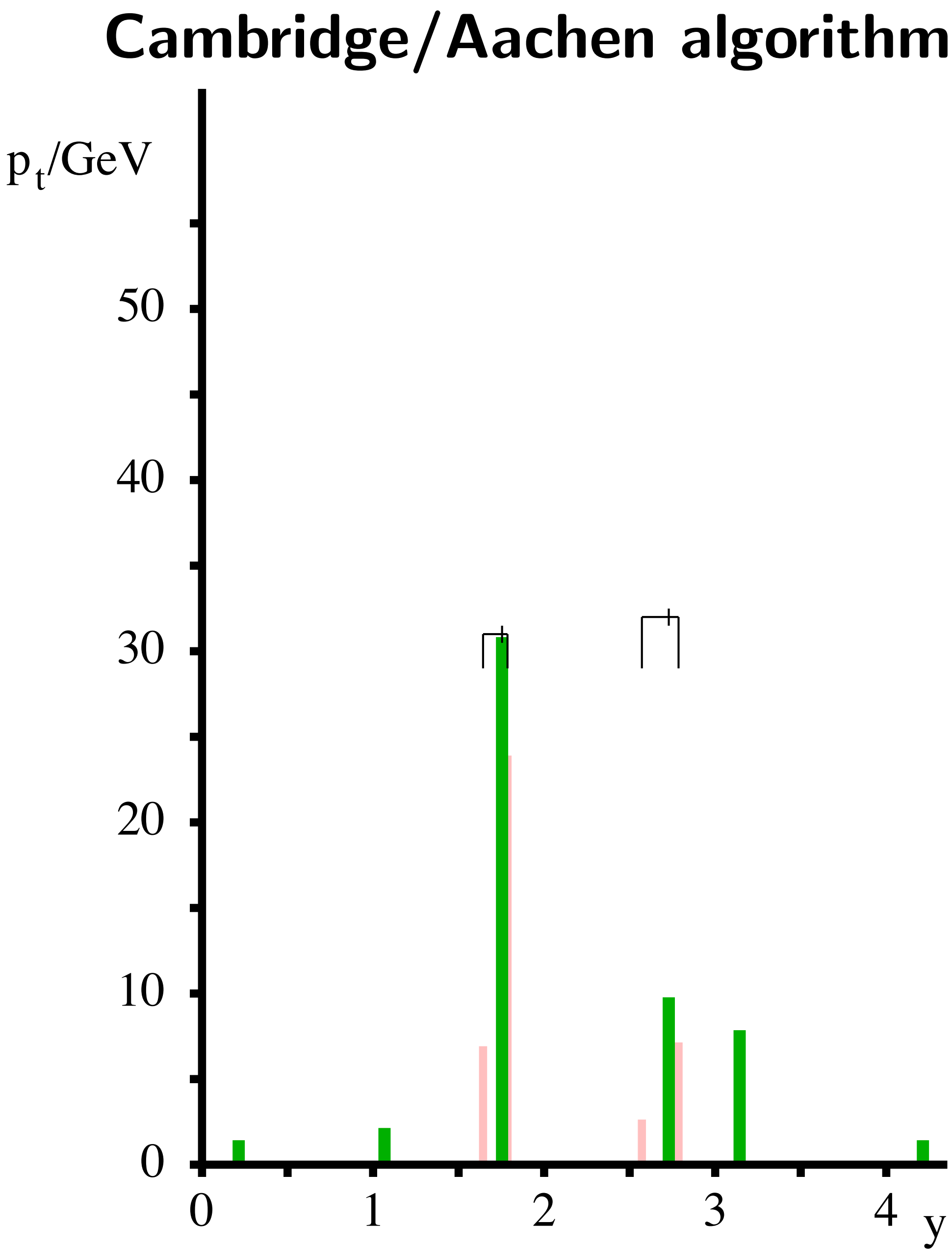

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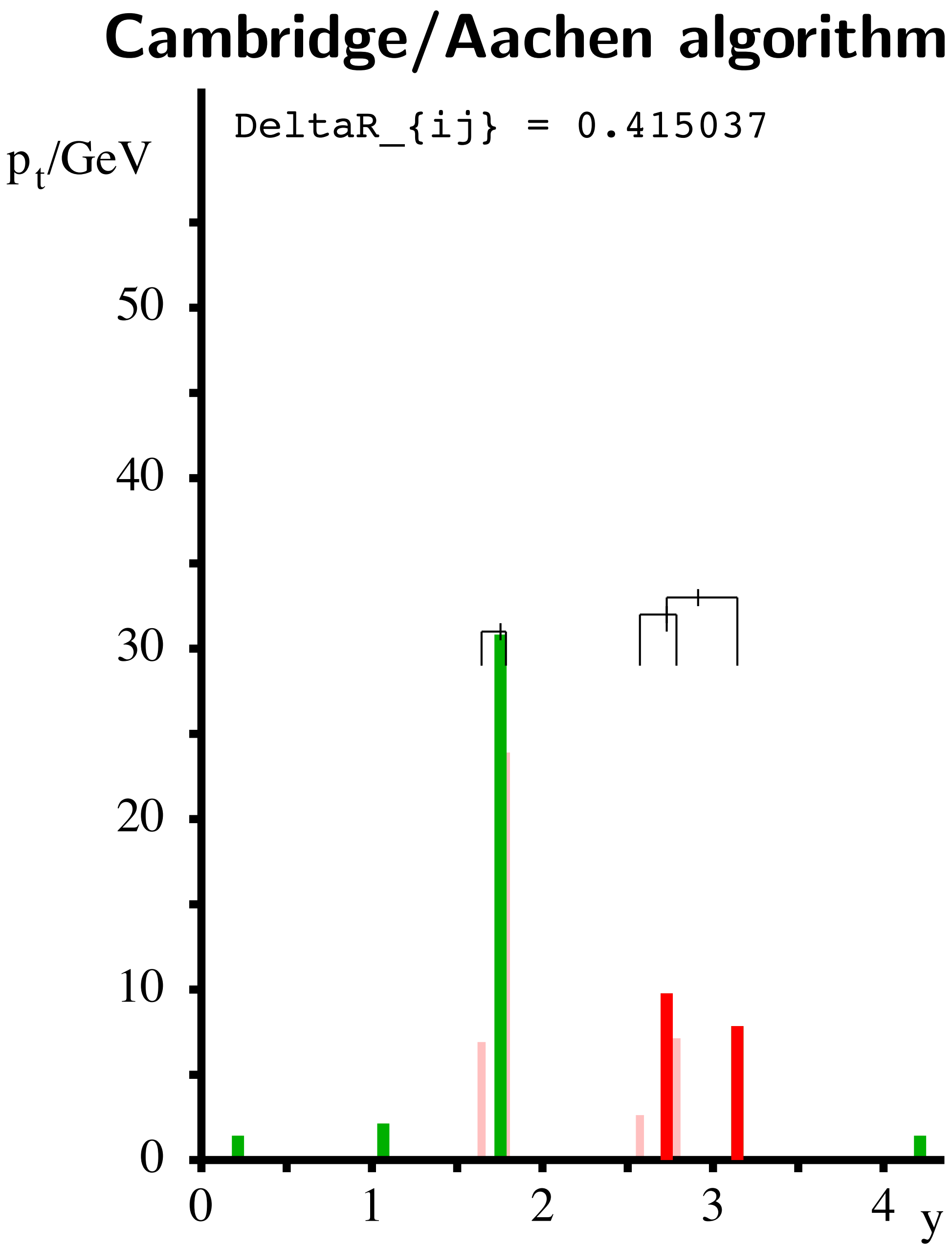

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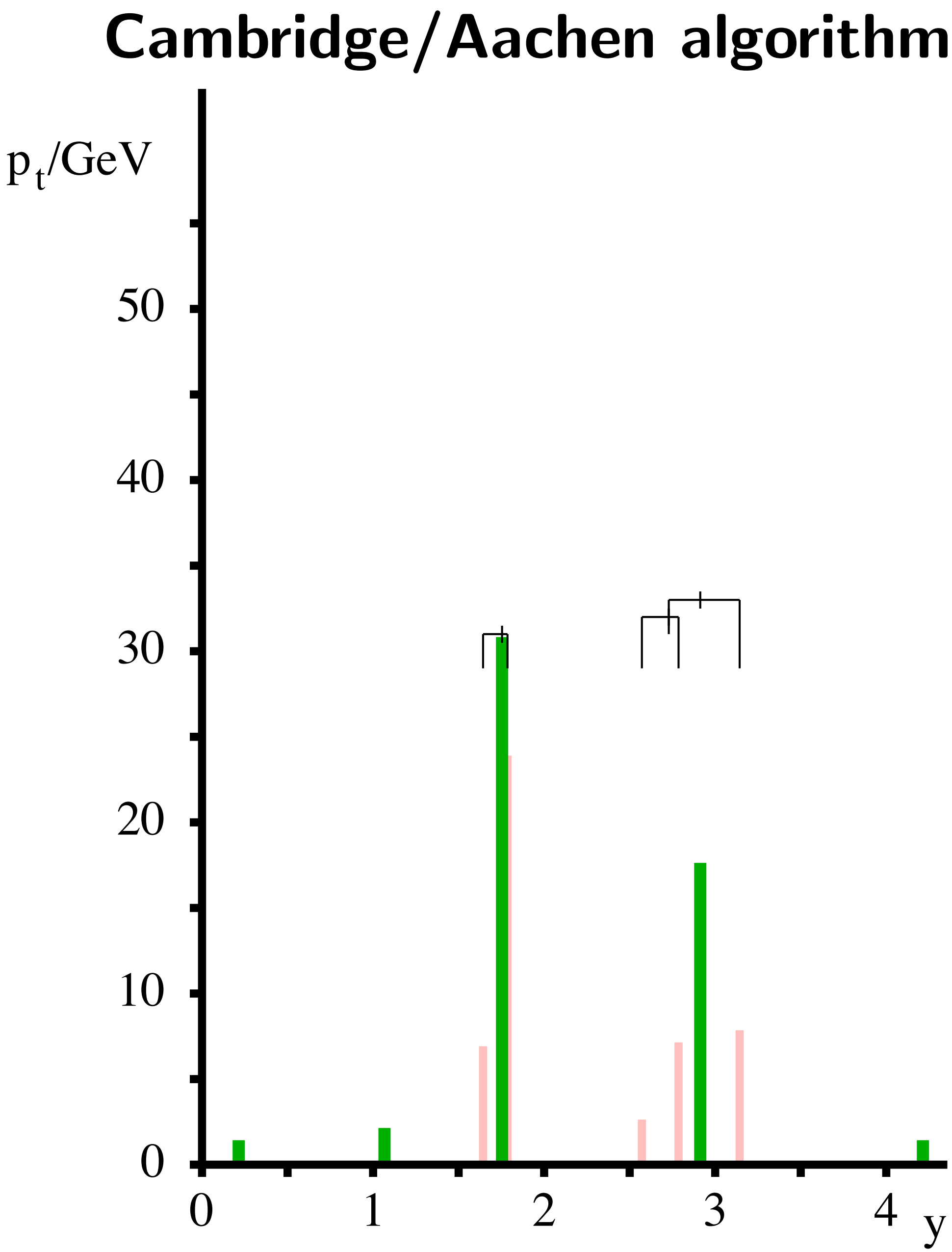

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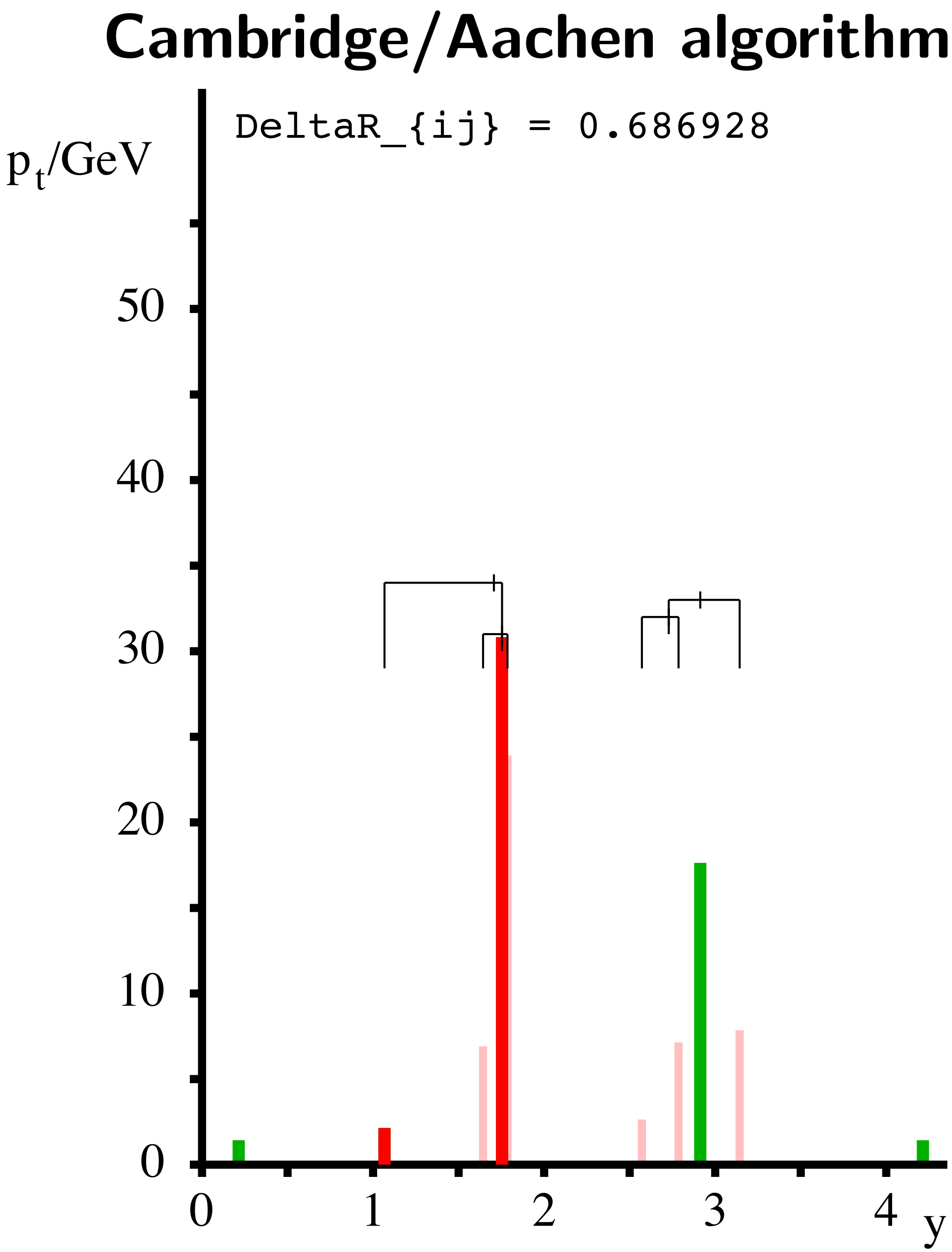

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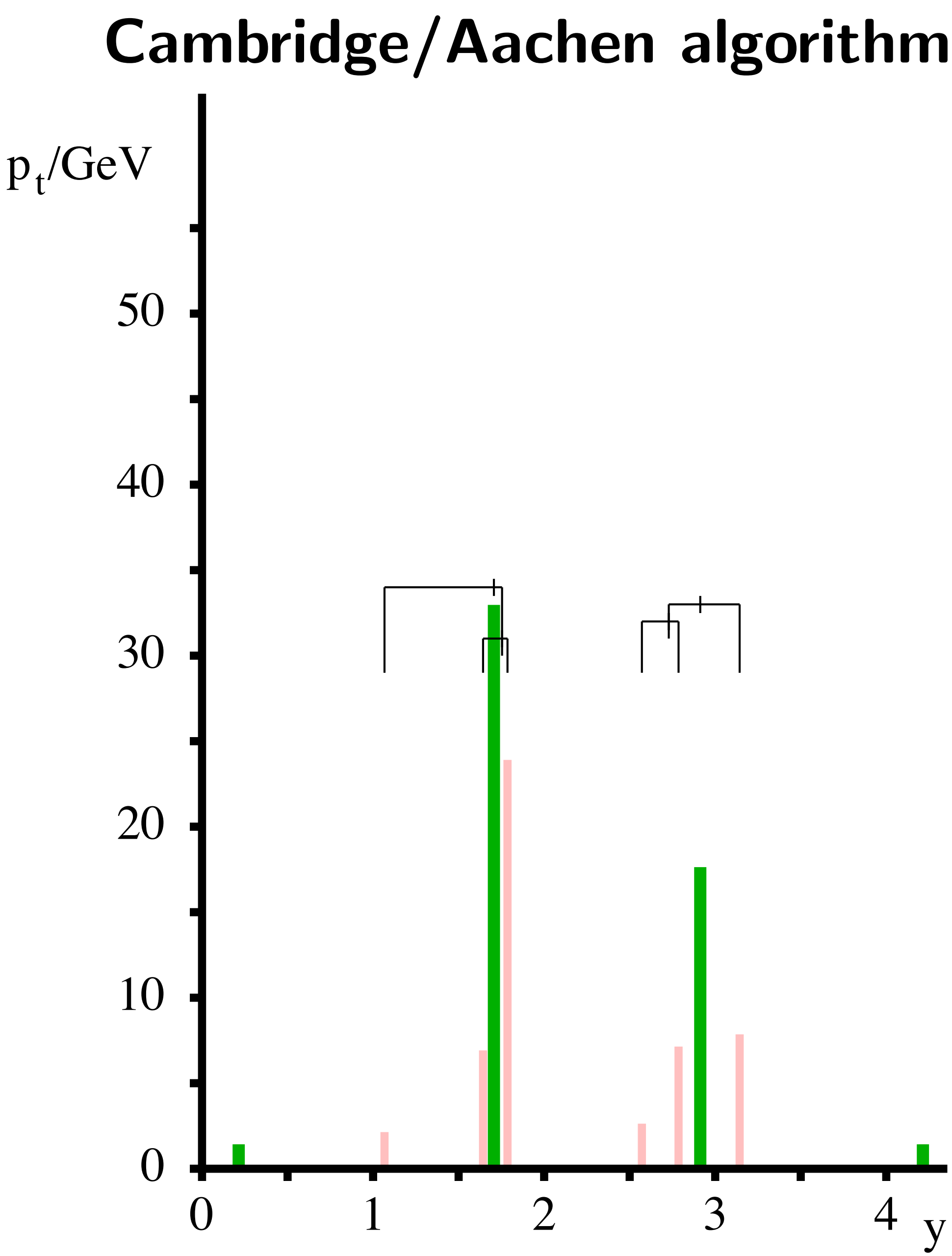

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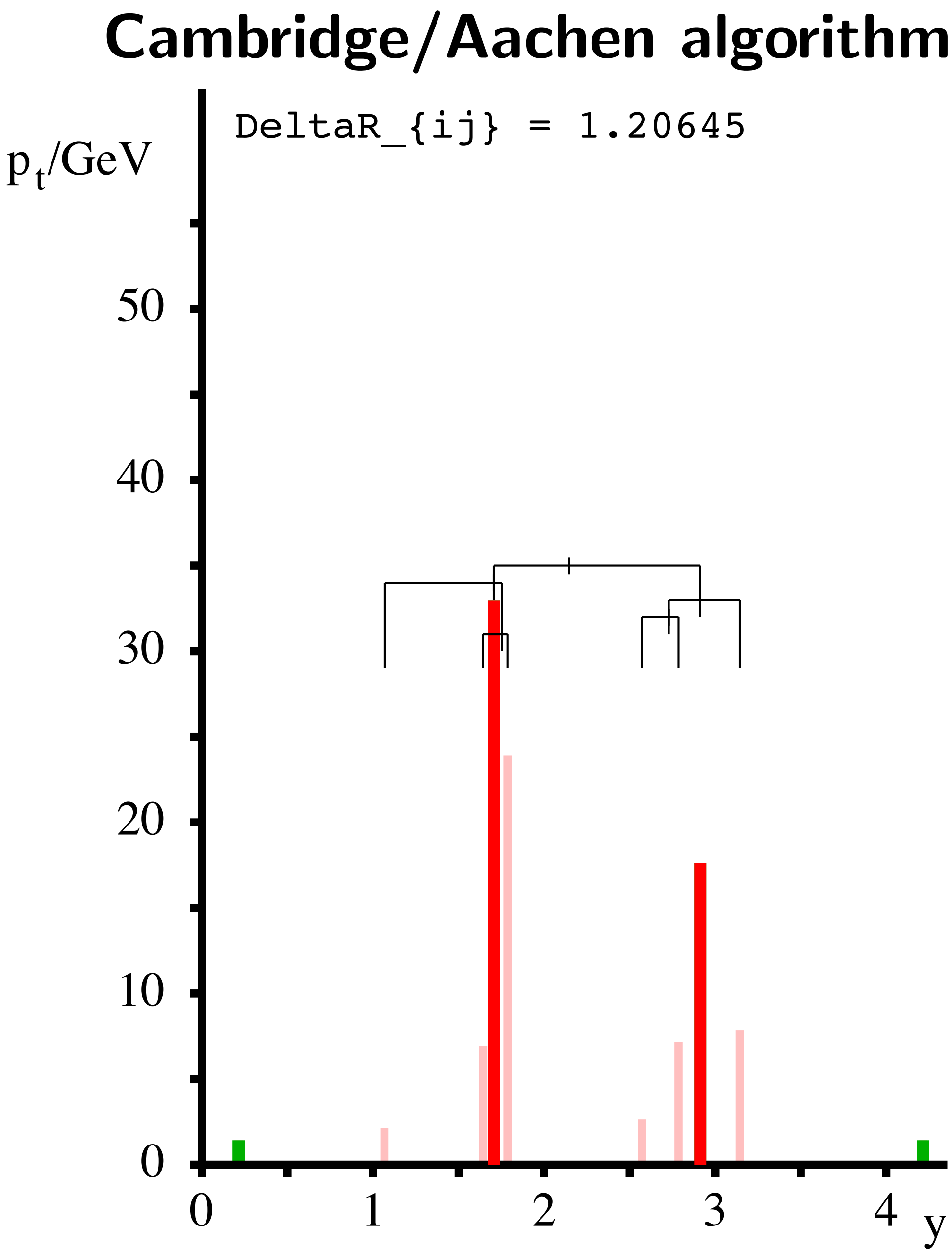
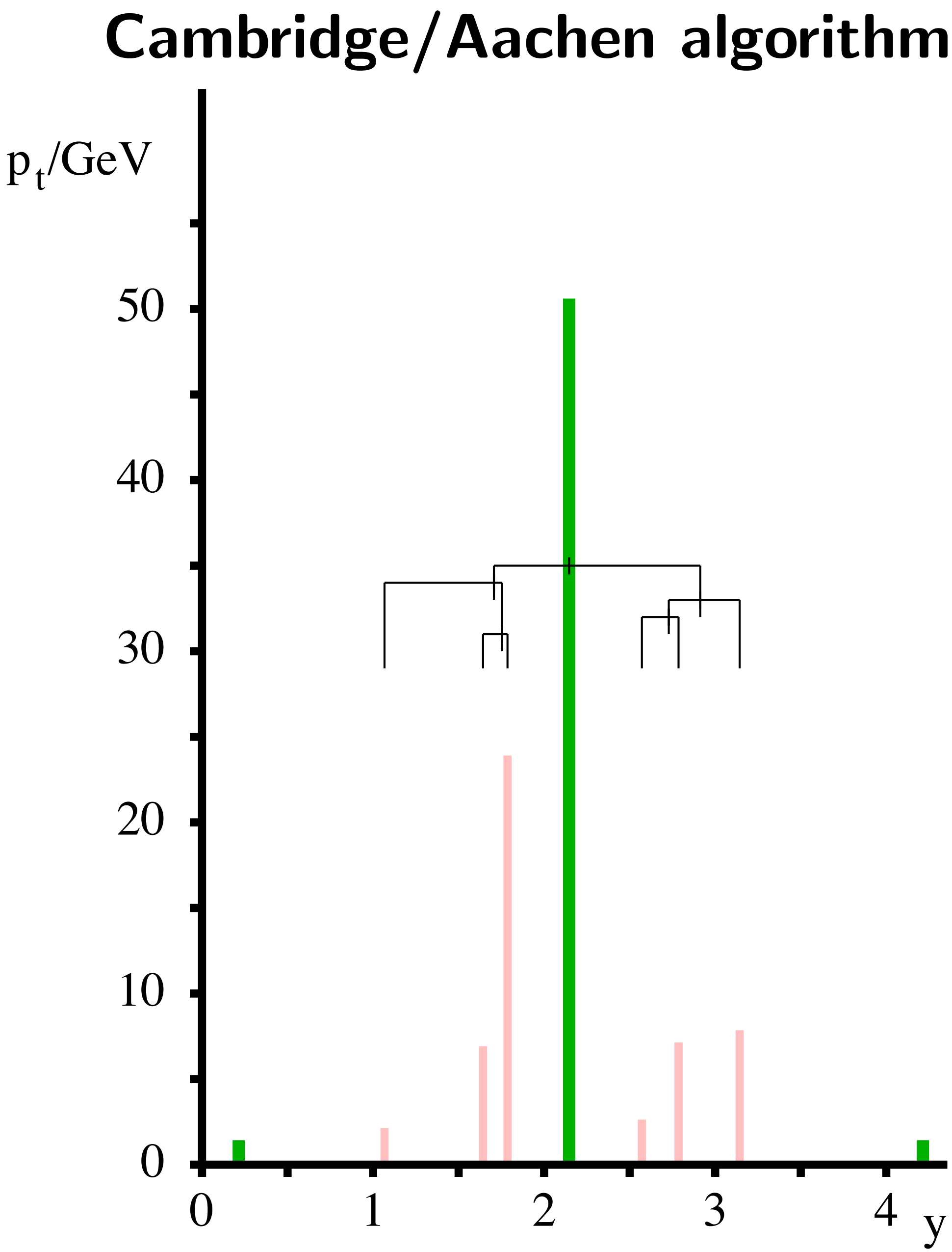
C/A identifies two hard blobs with limited soft contamination



How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them



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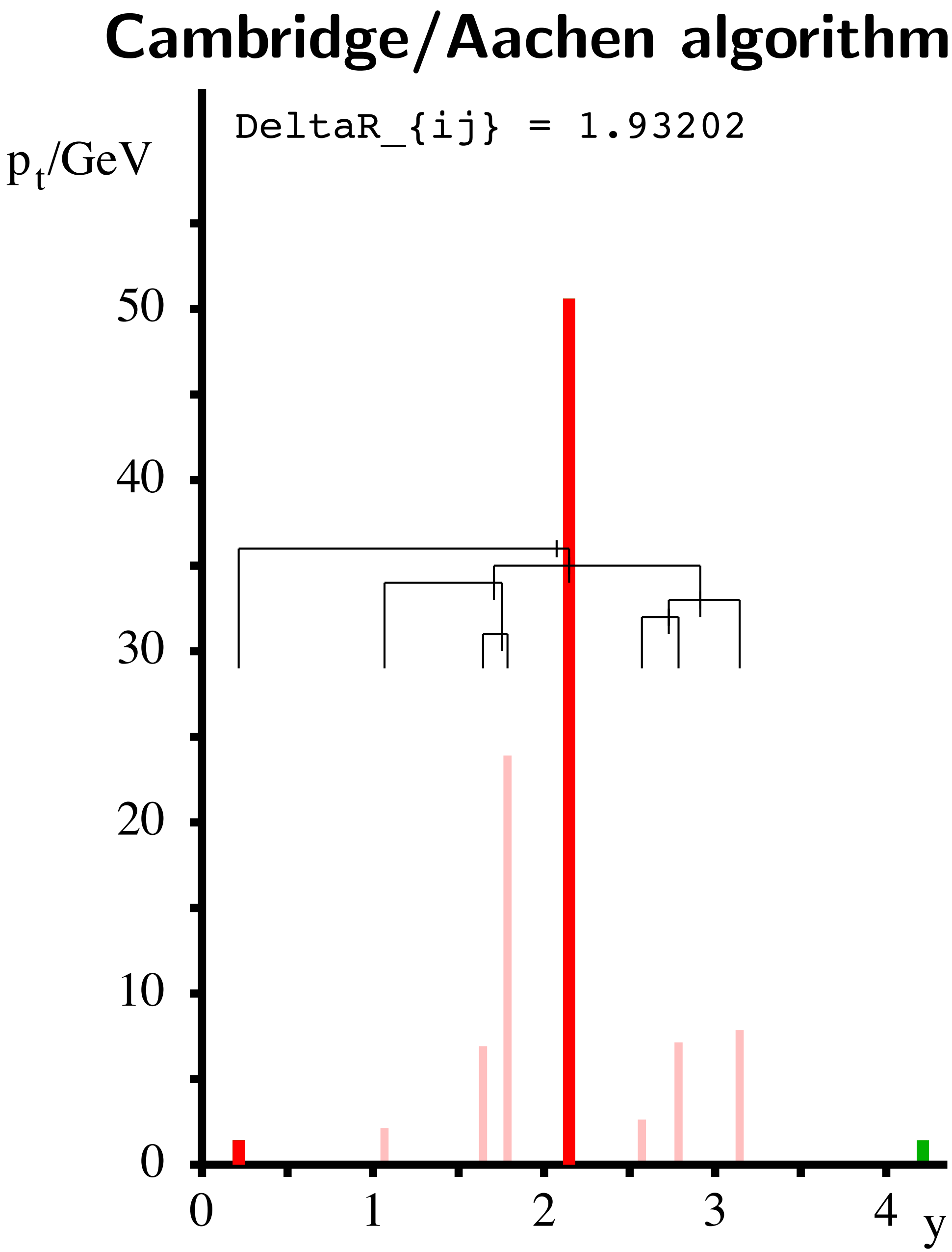
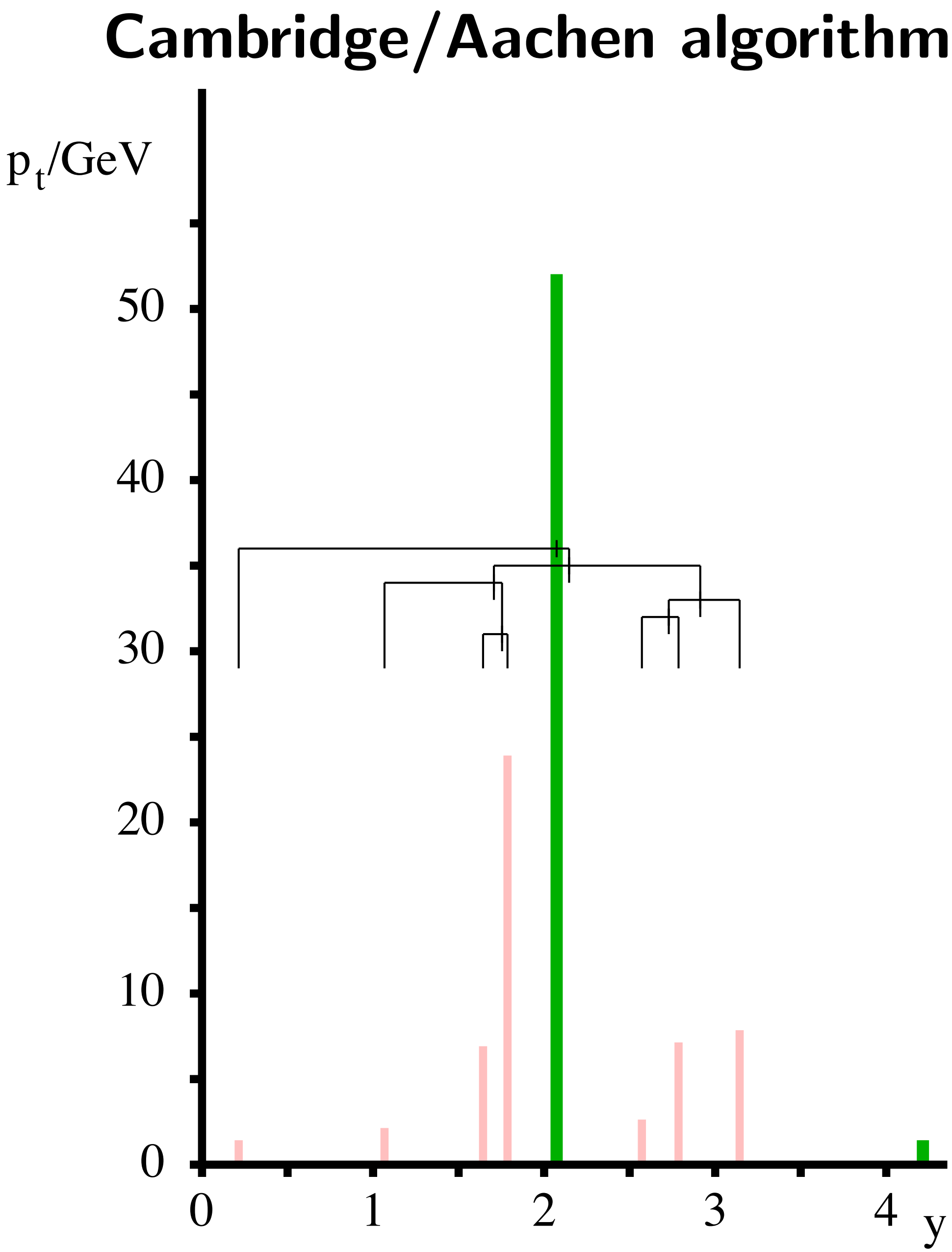


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them, and then adds in remaining soft junk



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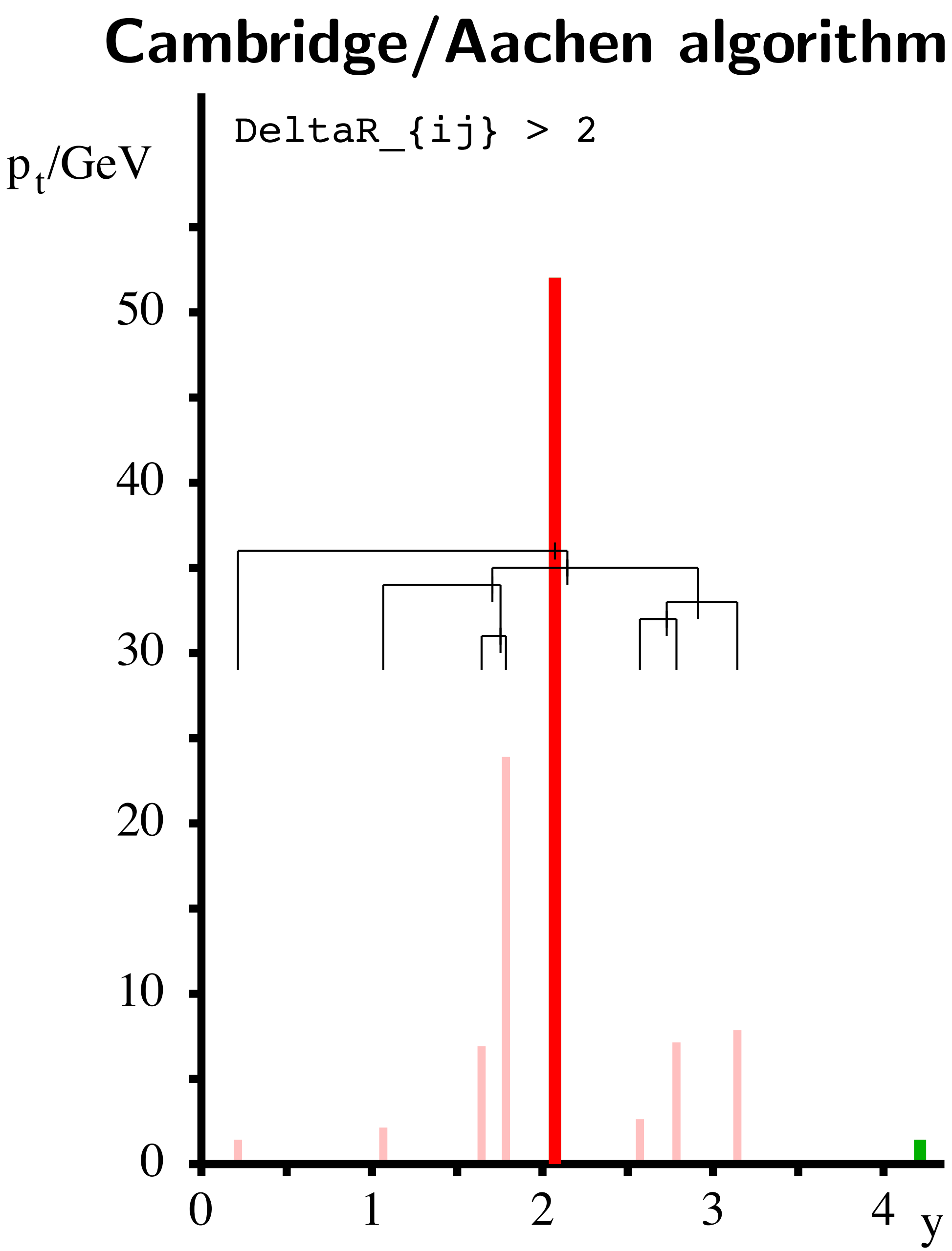

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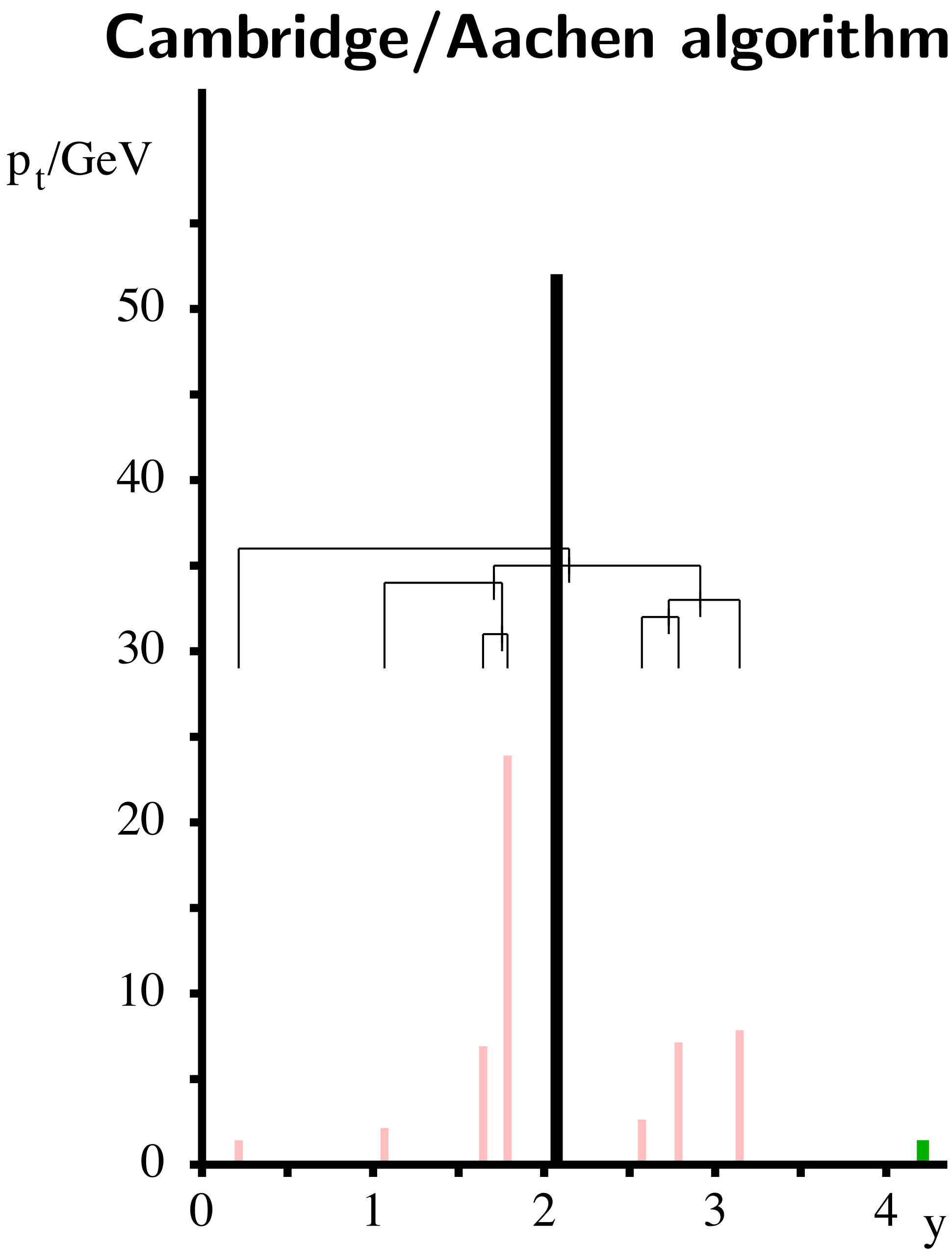

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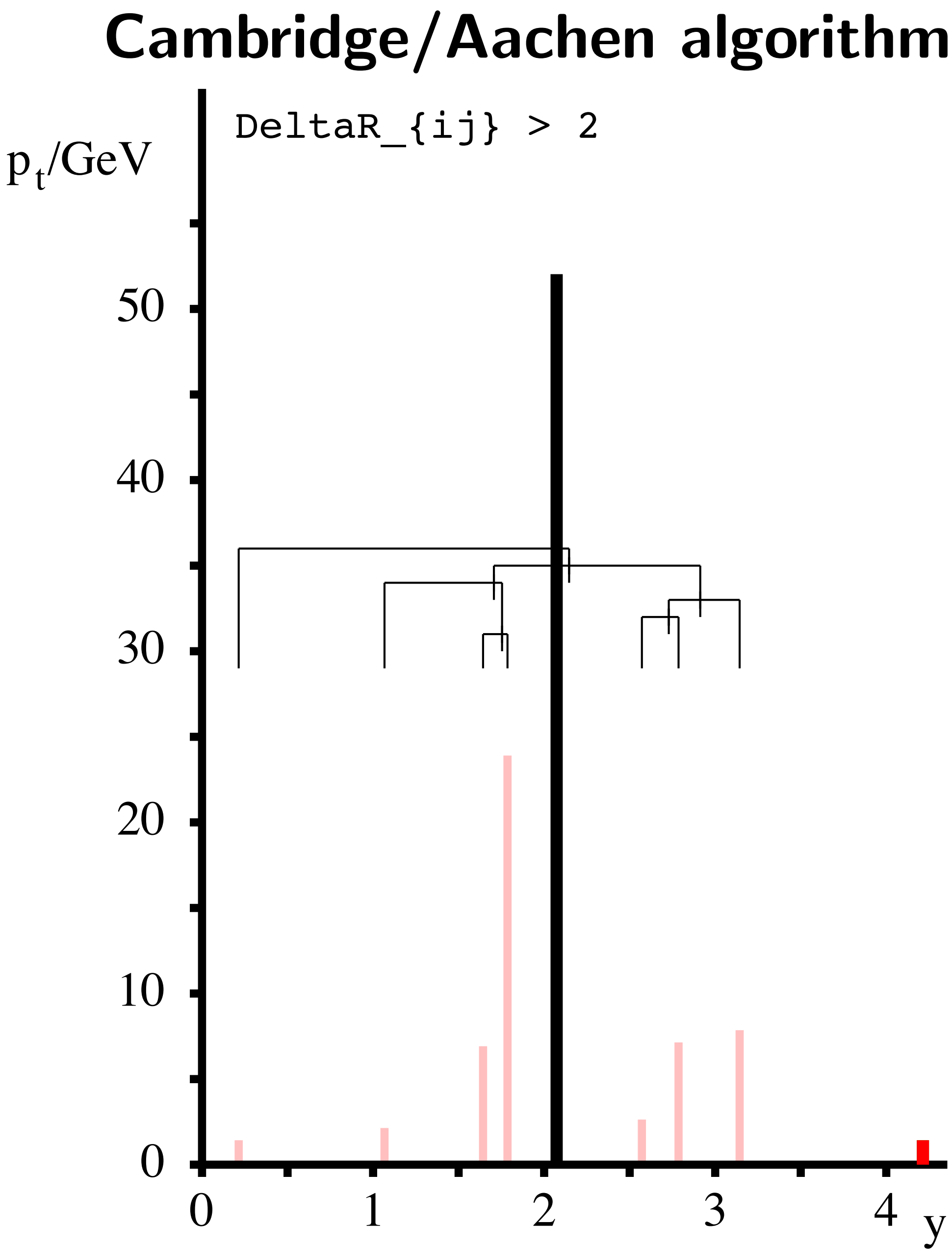

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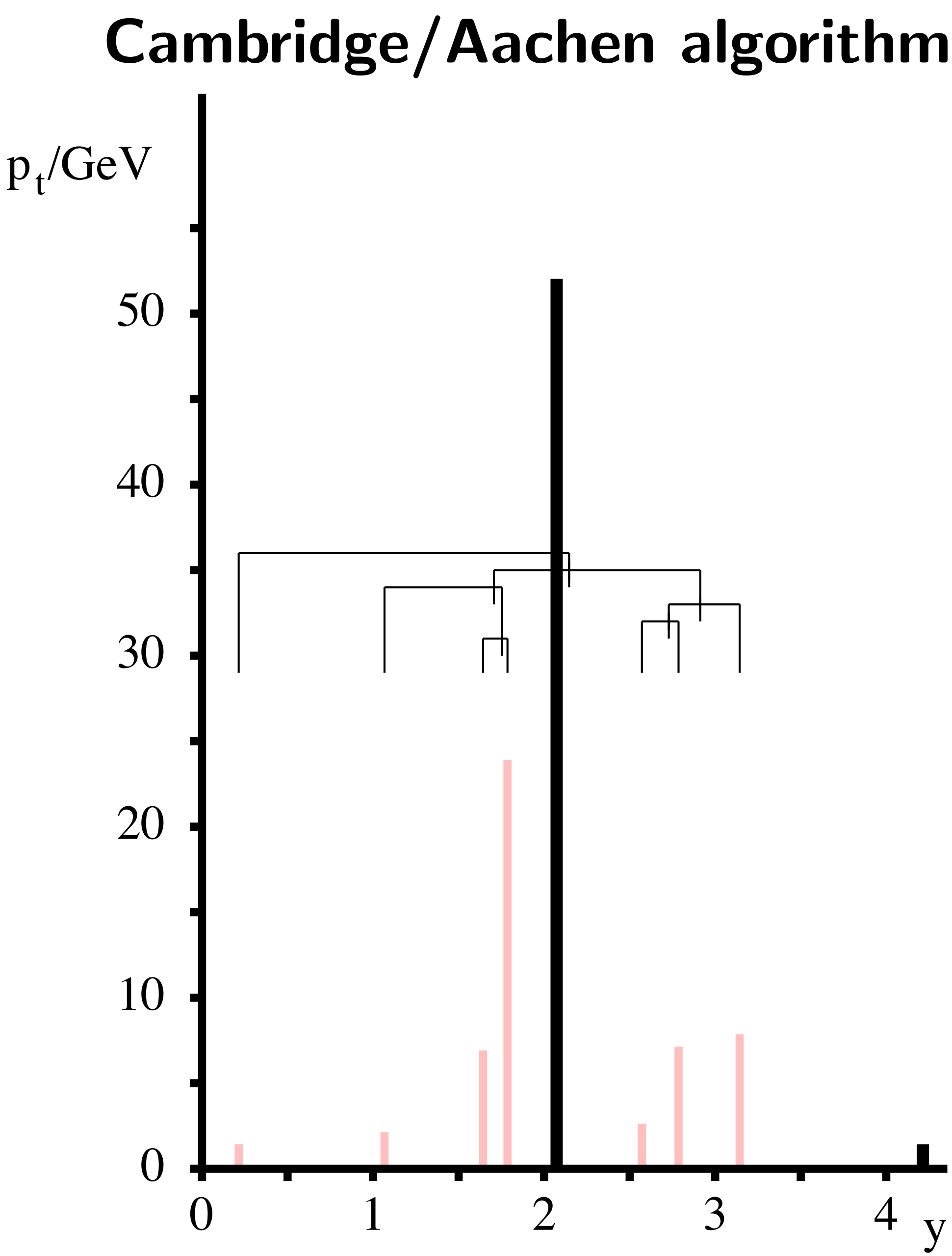


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

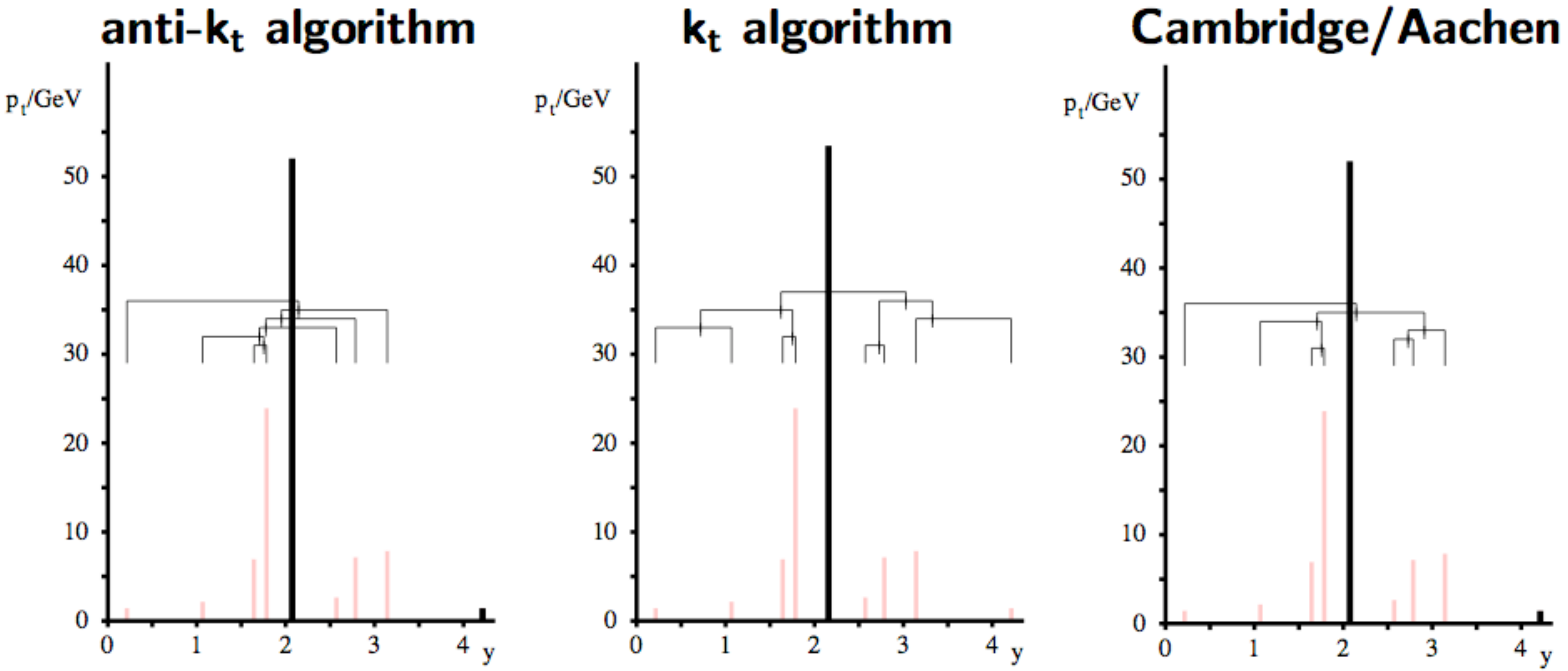
C/A identifies two hard blobs with limited soft contamination, joins them, and then adds in remaining soft junk

The interesting substructure is buried inside the clustering sequence — it's less contaminated by soft junk, but needs to be pulled out with special techniques

Butterworth, Davison, Rubin & GPS '08
Kaplan, Schwartz, Reherman & Tweedie '08
Butterworth, Ellis, Rubin & GPS '09
Ellis, Vermilion & Walsh '09

Slide by
Gavin Salam

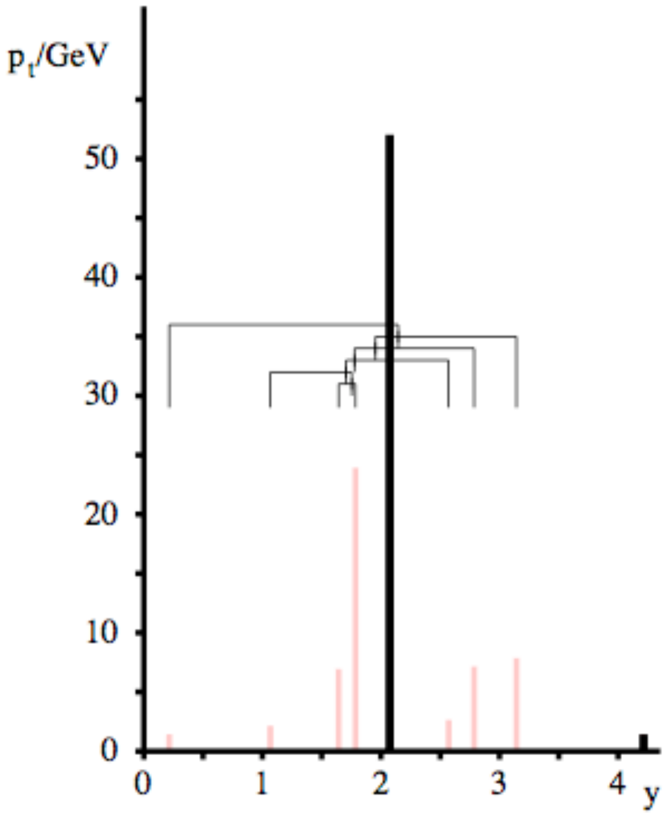
Hierarchical substructure



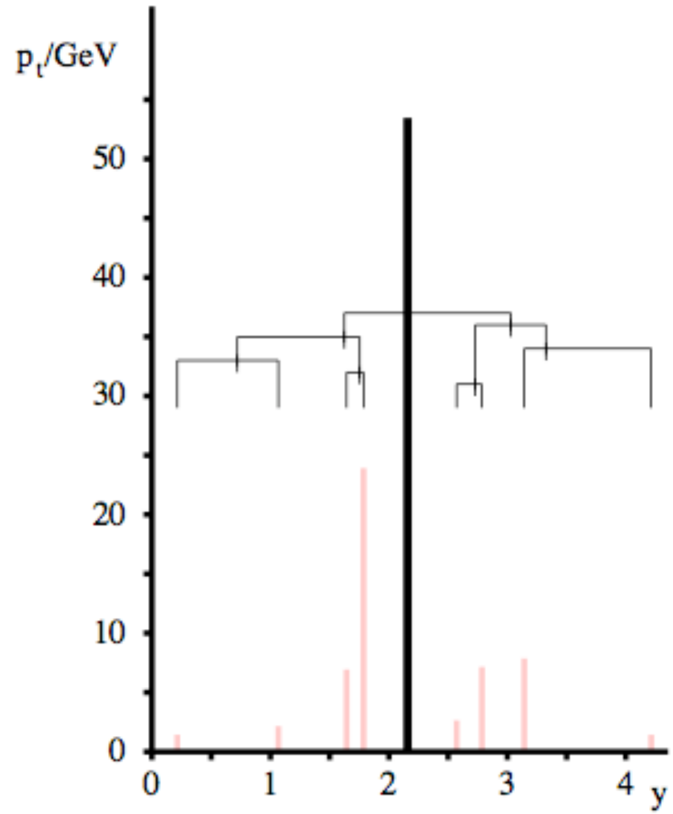
Slide by
Gavin Salam

Hierarchical substructure

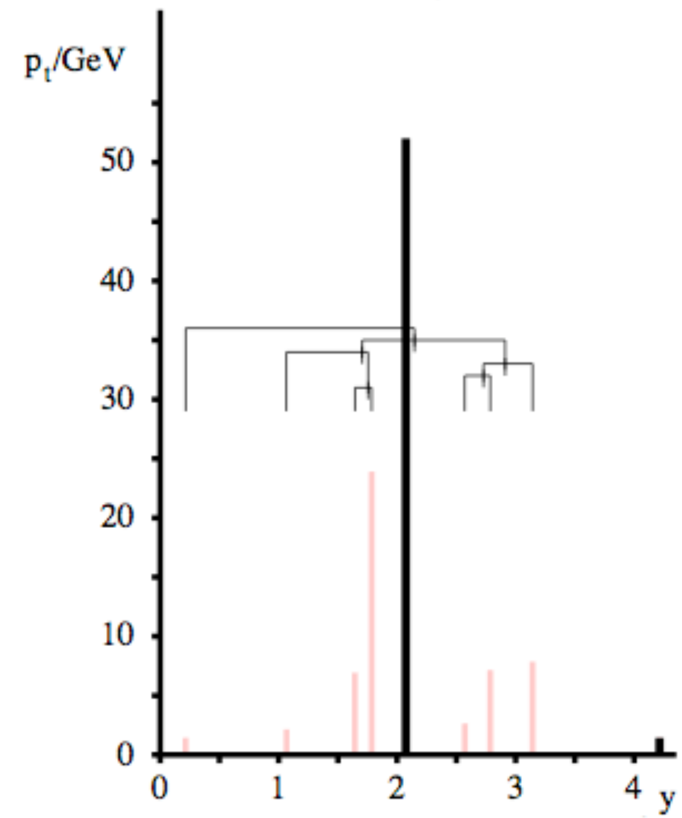
anti-k_t algorithm



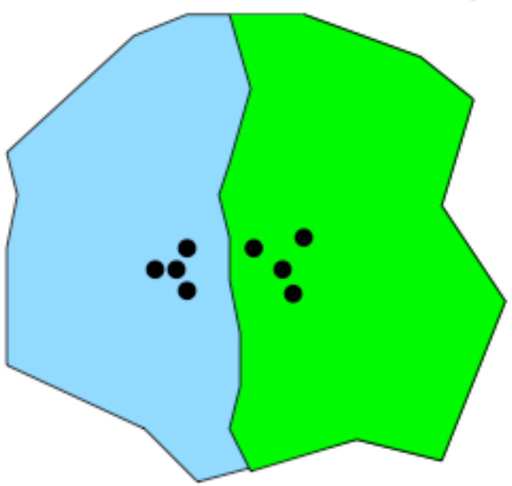
k_t algorithm

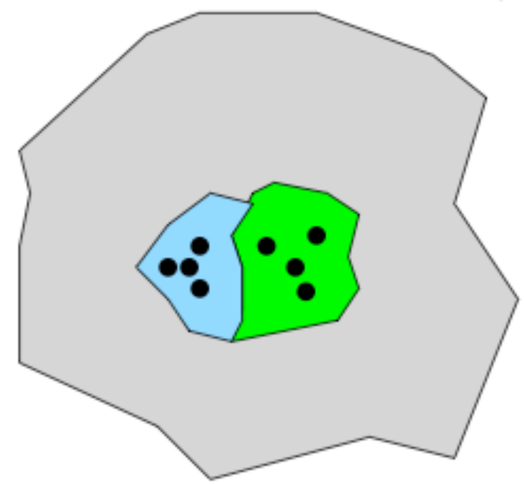


Cambridge/Aachen



Undo the last clustering step(s) →





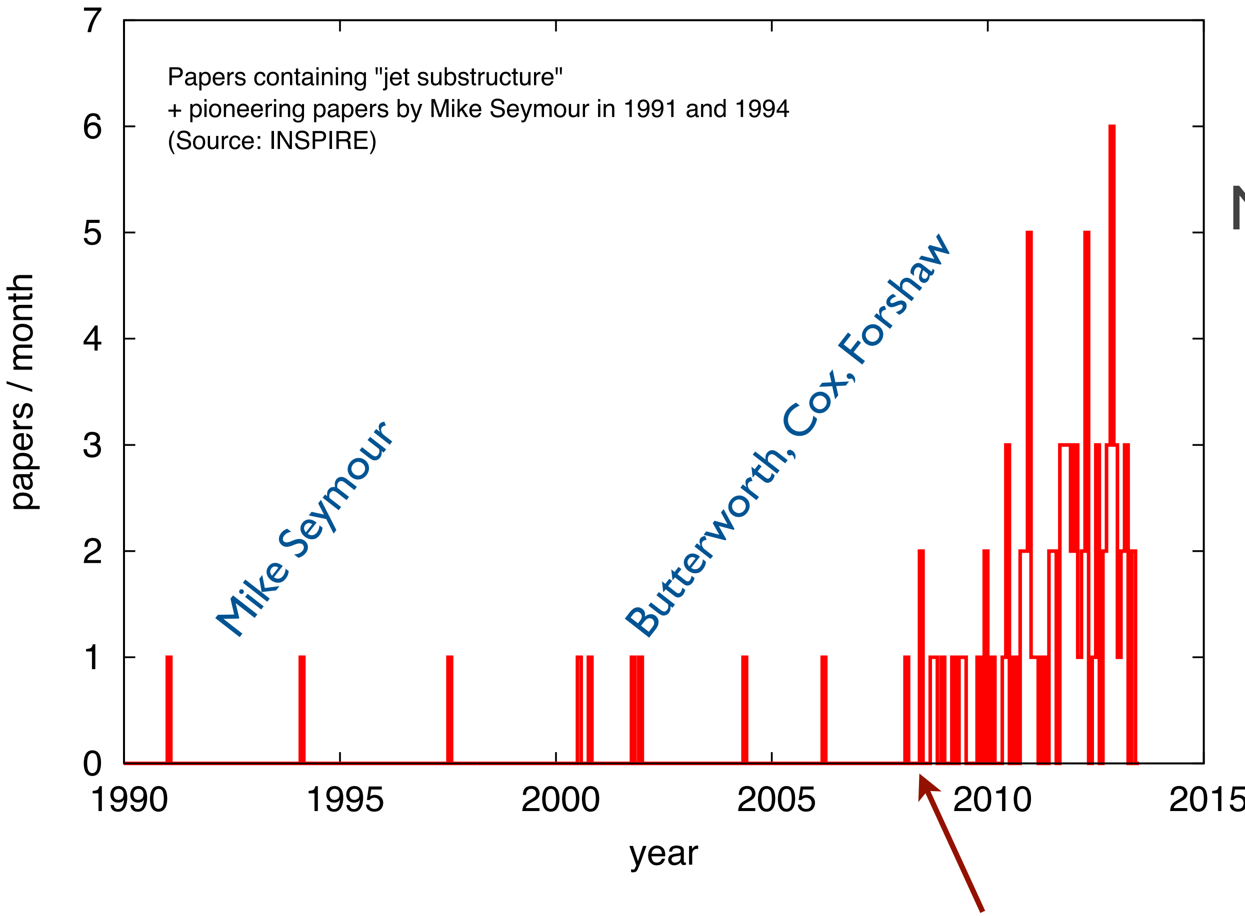
The IRC safe algorithms

	Speed	Regularity	UE contamination	Backreaction	Hierarchical substructure
k_t	☺ ☺ ☺	☂	☂☂	☁☁	☺ ☺
Cambridge /Aachen	☺ ☺ ☺	☂	☂	☁☁	☺ ☺ ☺
anti-k_t	☺ ☺ ☺	☺ ☺	☁/ ☺	☺ ☺	✘
SISCone	☺	☁	☺ ☺	☁	✘

Array of tools with different characteristics.
Pick the right one for the job

‘Jet substructure’ papers in INSPIRE

Number of papers containing the words ‘jet substructure’



More than 100 papers since 2008
(+ some background noise)

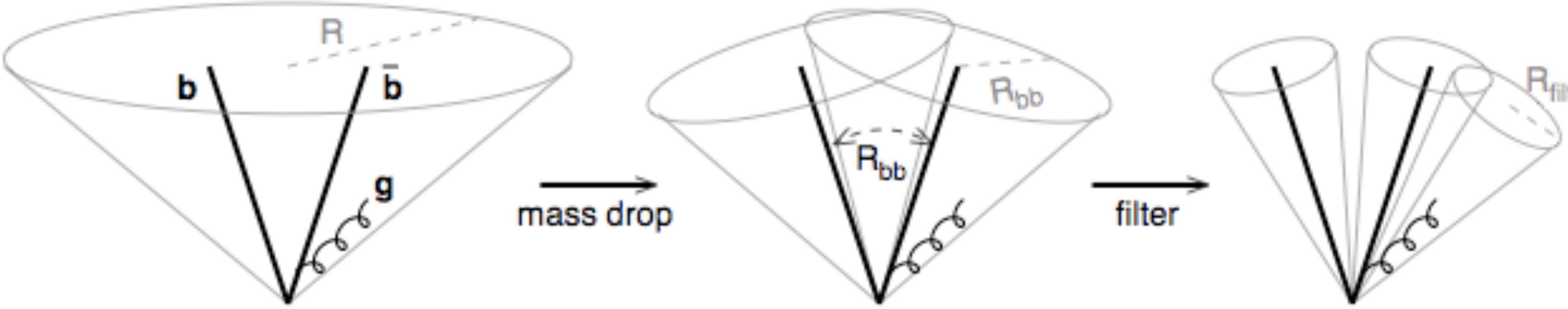
Pioneered by M. Seymour in the early ‘90s, rebooted by BDRS paper

15. **Jet substructure as a new Higgs search channel at the LHC.**
Jonathan M. Butterworth, Adam R. Davison (University Coll. London), Mathieu Rubin, Gavin P. Salam (Paris, LPTHE).
Published in **Phys.Rev.Lett. 100 (2008) 242001**
e-Print: **arXiv:0802.2470 [hep-ph]**

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$

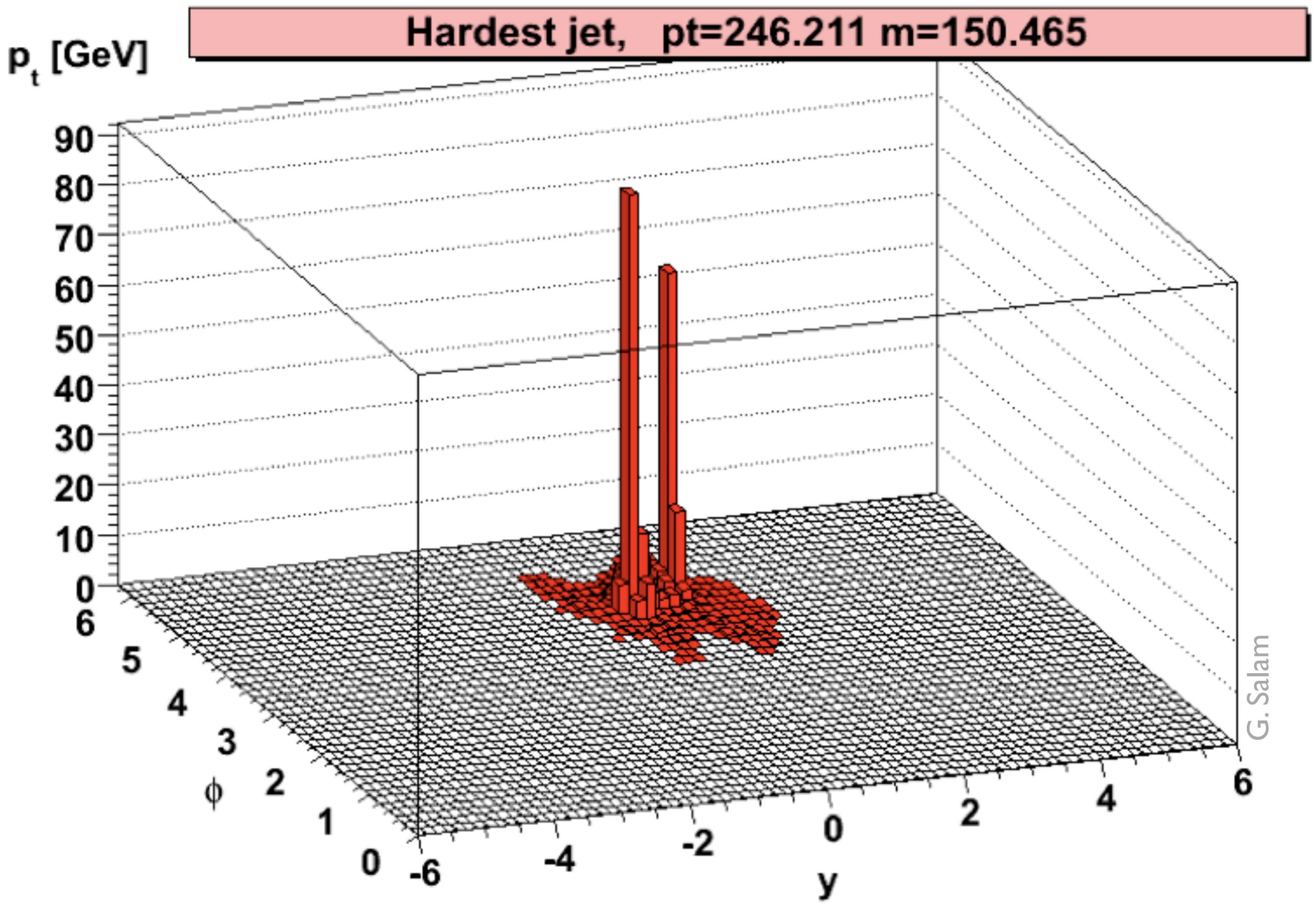
The BDRS tagger/groomer

Butterworth, Davison, Rubin, Salam, 2008



- A two-prong tagger/groomer for boosted Higgs, which
  - Uses the **Cambridge/Aachen** algorithm (because it's 'physical')
  - Employs a **Mass-Drop** condition, as well as an **asymmetry cut** to find the **relevant splitting** (i.e. '**tag**' the heavy particle)
  - Includes a post-processing step, using 'filtering' (introduced in the same paper) to clean as much as possible the resulting jets of UE contamination ('**grooming**')

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$

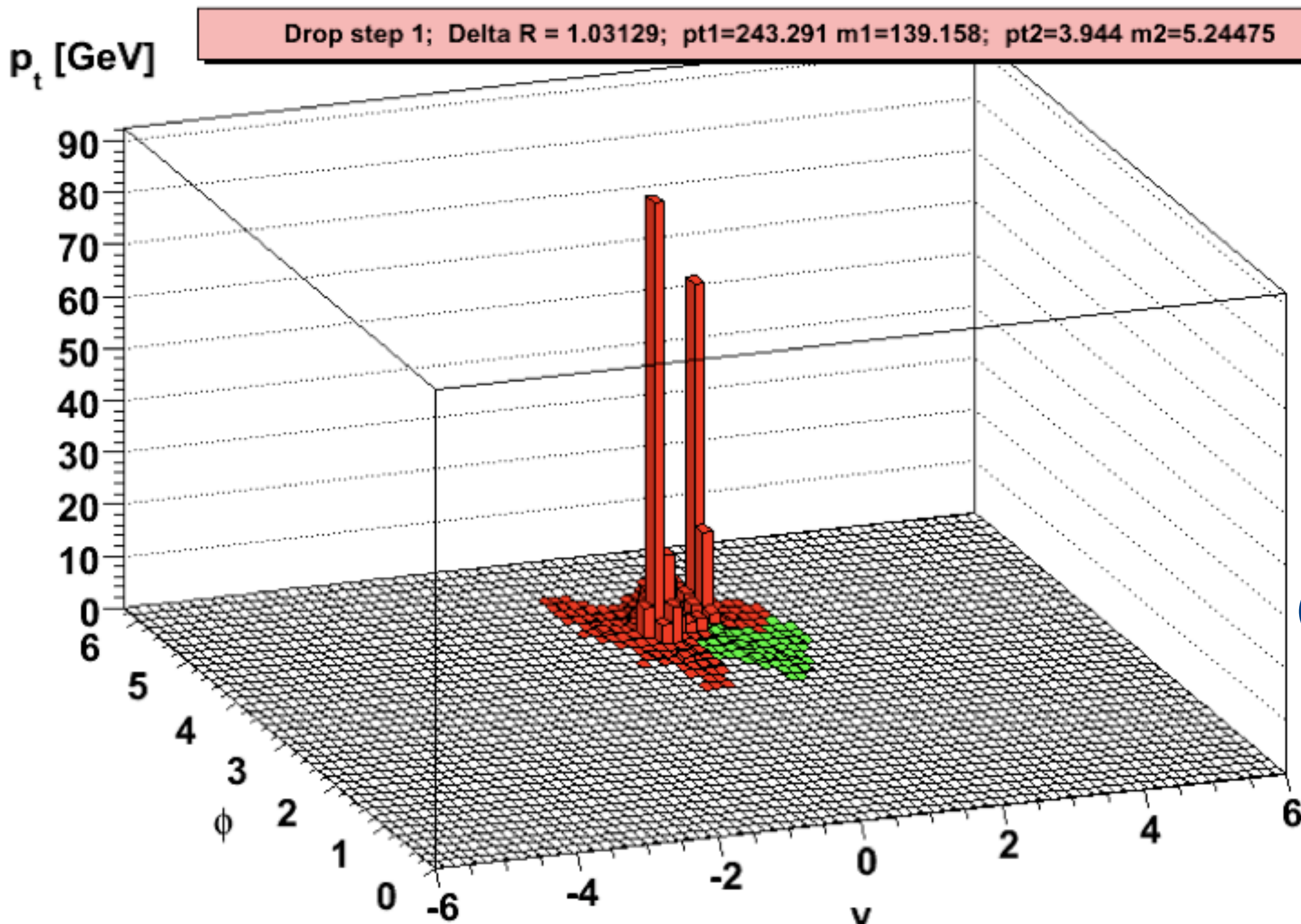


Start with the hardest jet

Use C/A with large R=1.2

m_j = 150 GeV

pp → ZH → ννbb

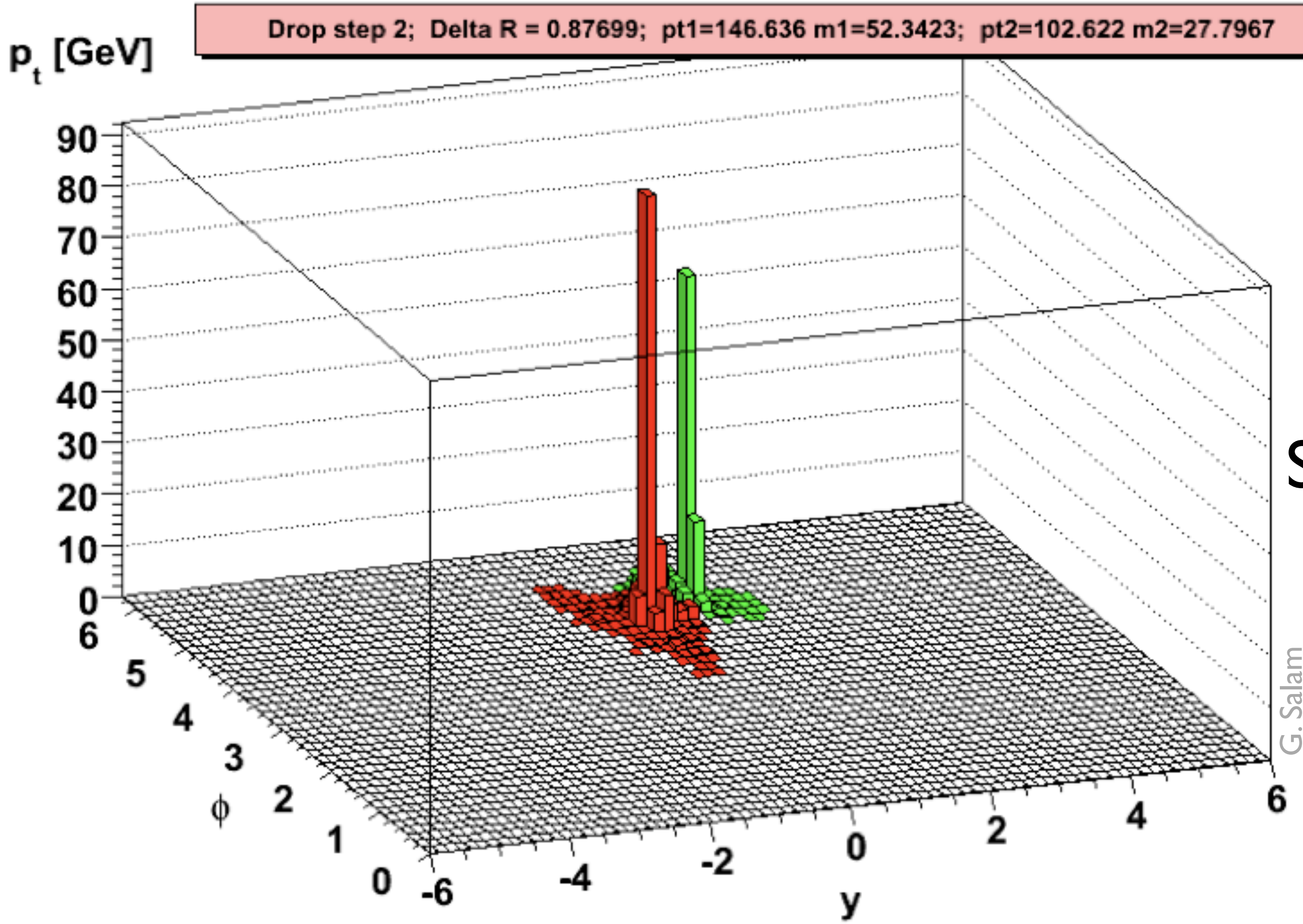


Undo last step of clustering

Check how the mass splits between the two subjets (m_1 = 139 GeV, m_2 = 5 GeV) and how asymmetric the splitting is

If $\frac{max(m_1, m_2)}{m_j} > \mu$ or $\frac{min(p_{t1}^2, p_{t2}^2)}{m_j^2} \Delta R_{12}^2 < y_{cut}$ repeat

$pp \to ZH \to \nu\nu bb$

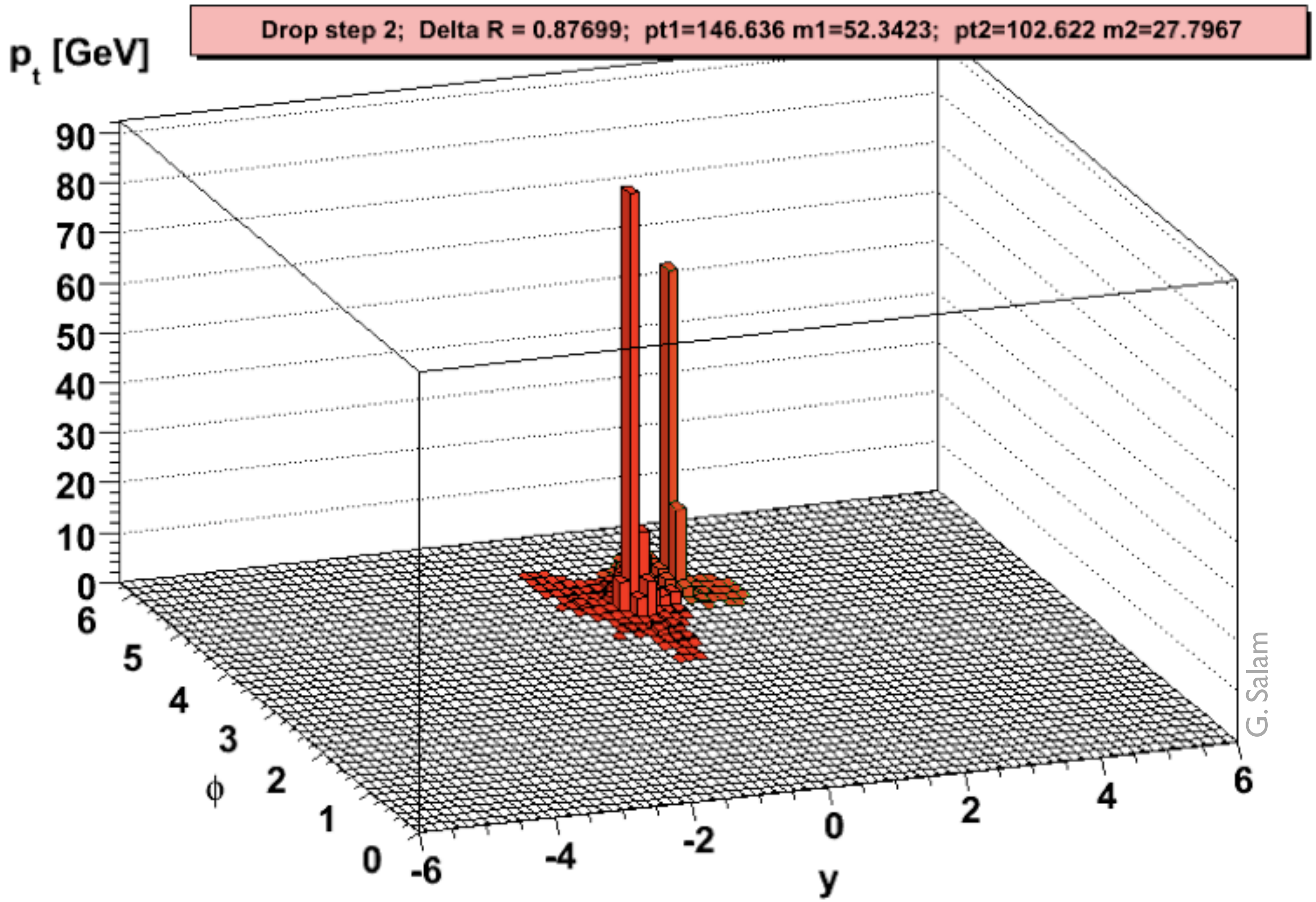


m_1 = 52 GeV, m_2 = 28 GeV

Stop when a large mass drop is observed

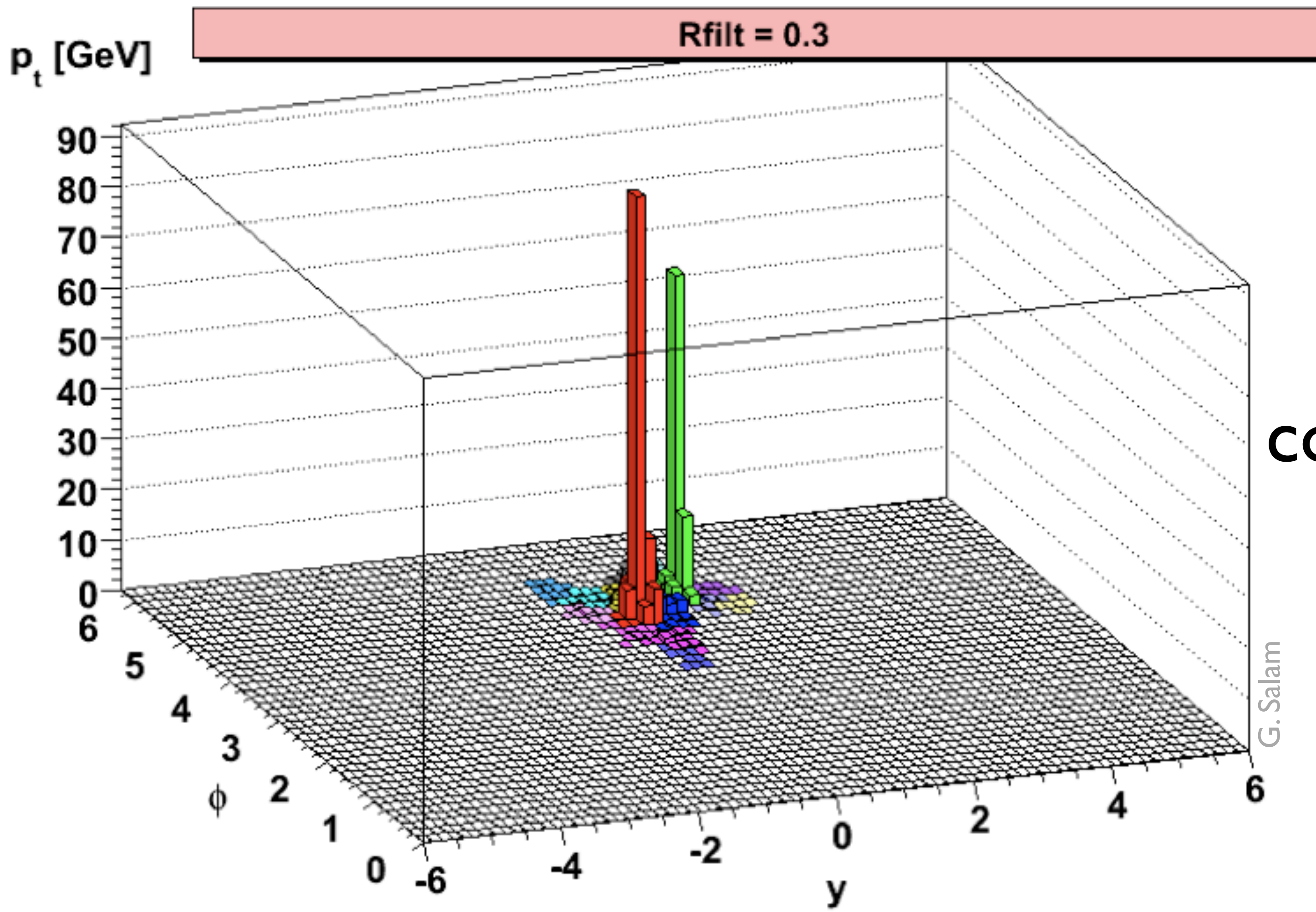
(and **recombine** these two jets)

[NB. Parameters used μ = 0.67 and y_{cut} = 0.09] pp →ZH → ννbb



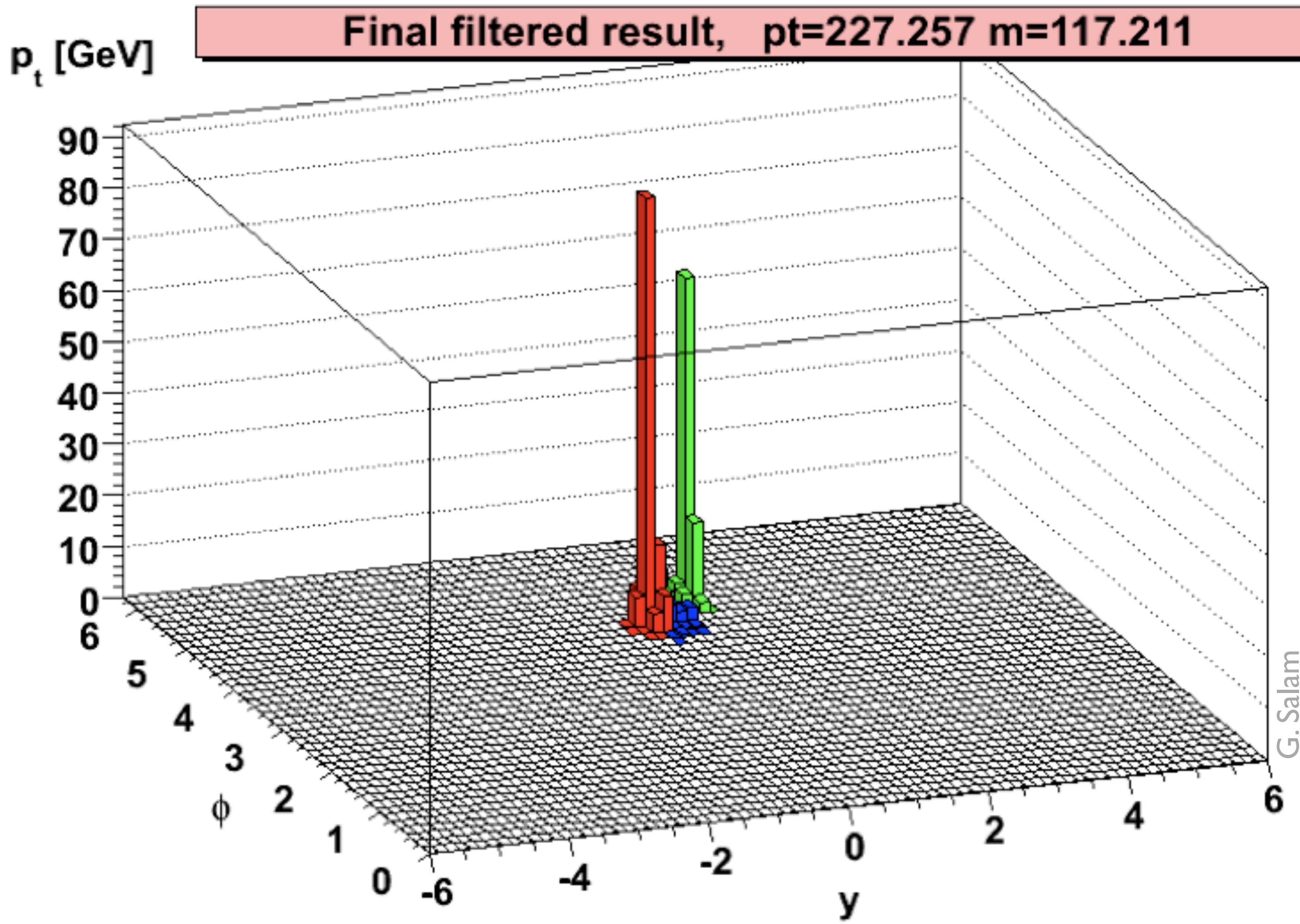
Start with the recombined jet

$pp \to ZH \to \nu\nu bb$



Recluster the contituents with R_{filt}

$pp \to ZH \to \nu\nu bb$



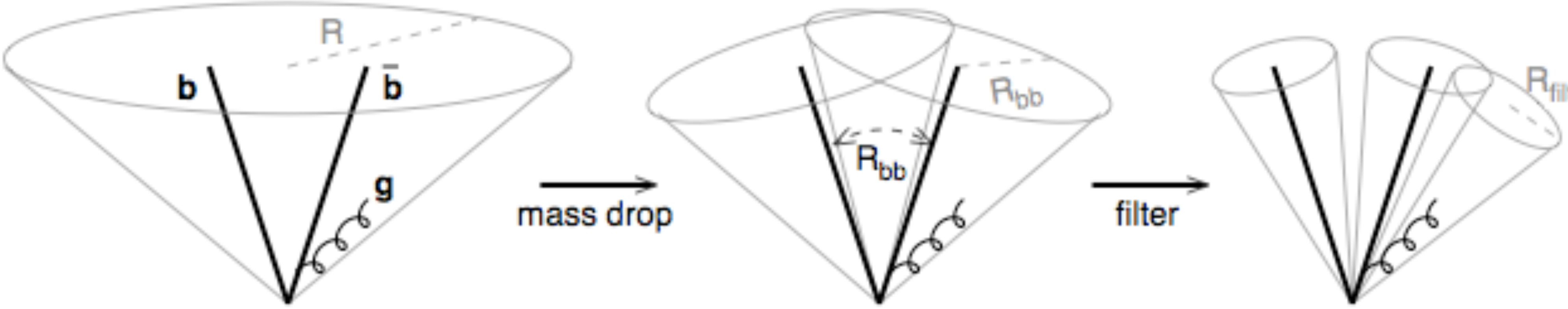
Only keep the n_{filt} hardest jets

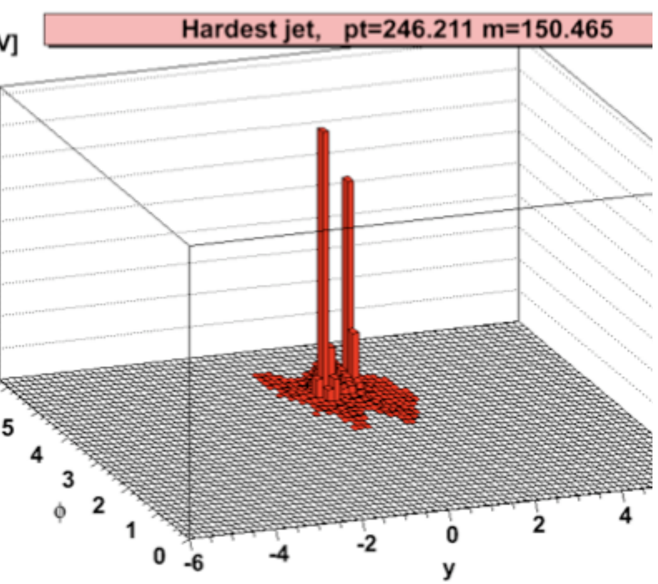
The low-momentum stuff surrounding the hard particles has been removed

Visualisation of BDRS

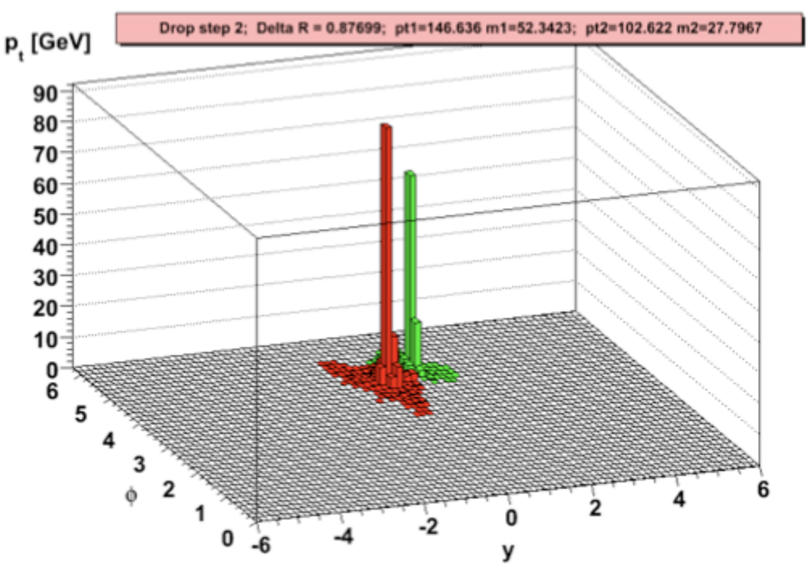
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$

Butterworth, Davison, Rubin, Salam, 2008

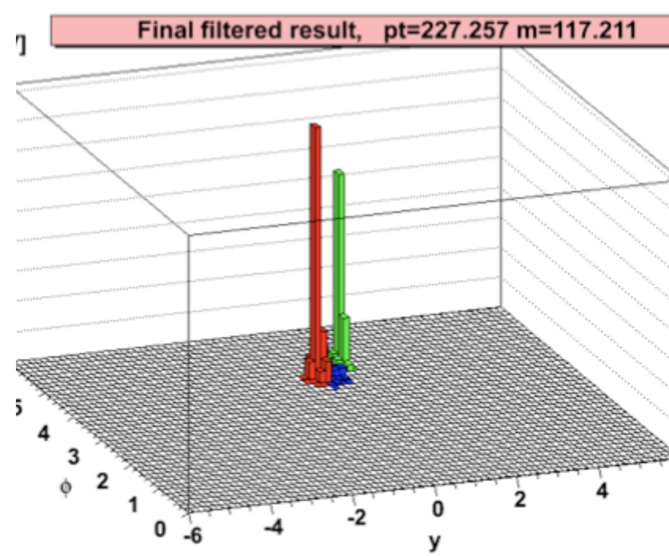




Cluster with a large R



Undo the clustering into subjets, until a large asymmetry/mass drop is observed: tagging step



Re-cluster with smaller R, and keep only 3 hardest jets: grooming step

First taggers/groomers

- **Mass Drop + Filtering** — Butterworth, Davison, Rubin, Salam, 2008

  Decluster with mass drop and asymmetry conditions
  Recluster constituents into subjets at distance scale R_{filt}, retain n_{filt} hardest subjets

- **Jet 'trimming'** — Krohn, Thaler, Wang, 2009

  Recluster constituents into subjets at distance scale R_{trim},
  retain subjets with $p_{t,subjet} > \varepsilon_{trim}\ p_{t,jet}$

- **Jet 'pruning'** — S. Ellis, Vermilion, Walsh, 2009

  While building up the jet, discard softer subjets when $\Delta R > R_{prune}$
  and $\min(p_{t1},p_{t2}) < \varepsilon_{prune}\ (p_{t1}+p_{t2})$

Aim: limit contamination from QCD background while retaining bulk of perturbative radiation

Trimming and pruner are a priori groomers, but can become taggers when combined with an invariant mass window test
(if you can groom away everything then there's no heavy particle in the jet)

Soft Drop declustering

Larkoski, Marzani, Soyez, Thaler, 2014

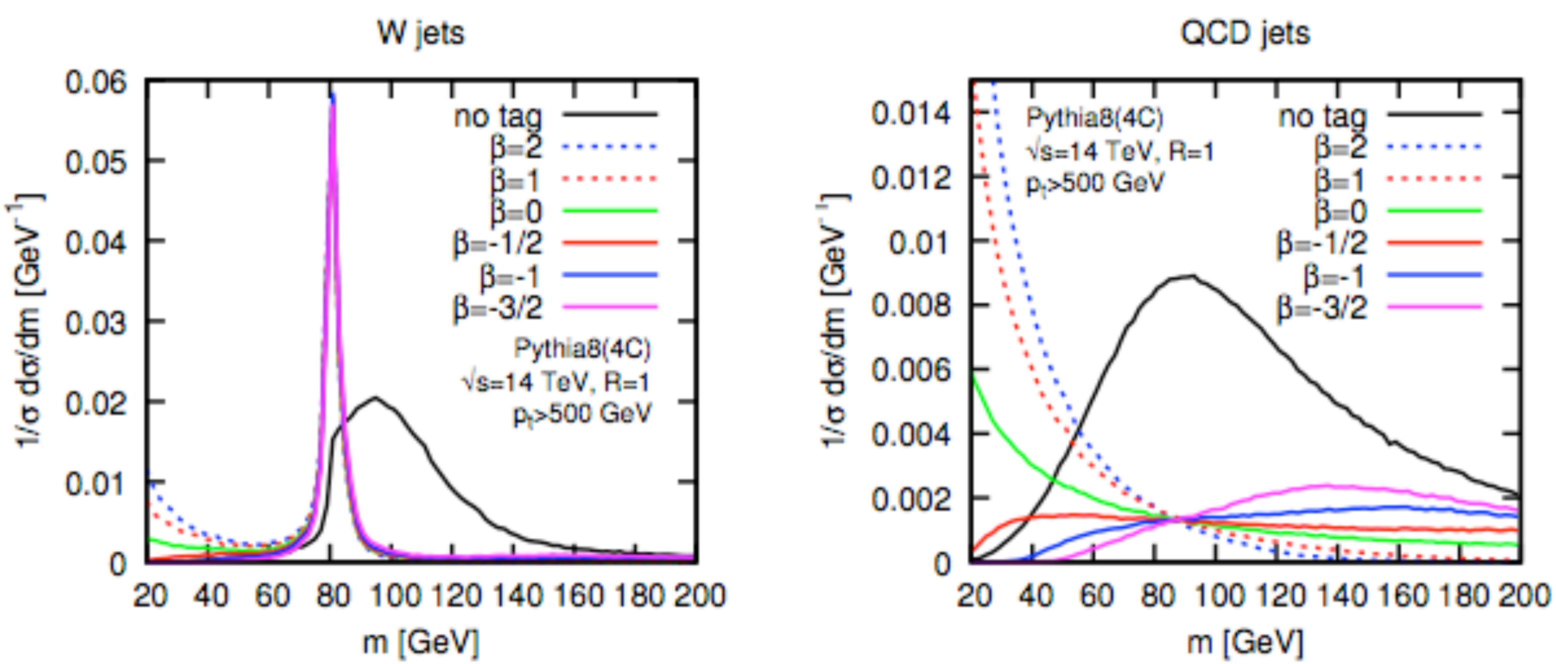
Decluster and drop softer constituent unless

$$\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

i.e. remove wide-angle soft radiation from a jet

The paper contains

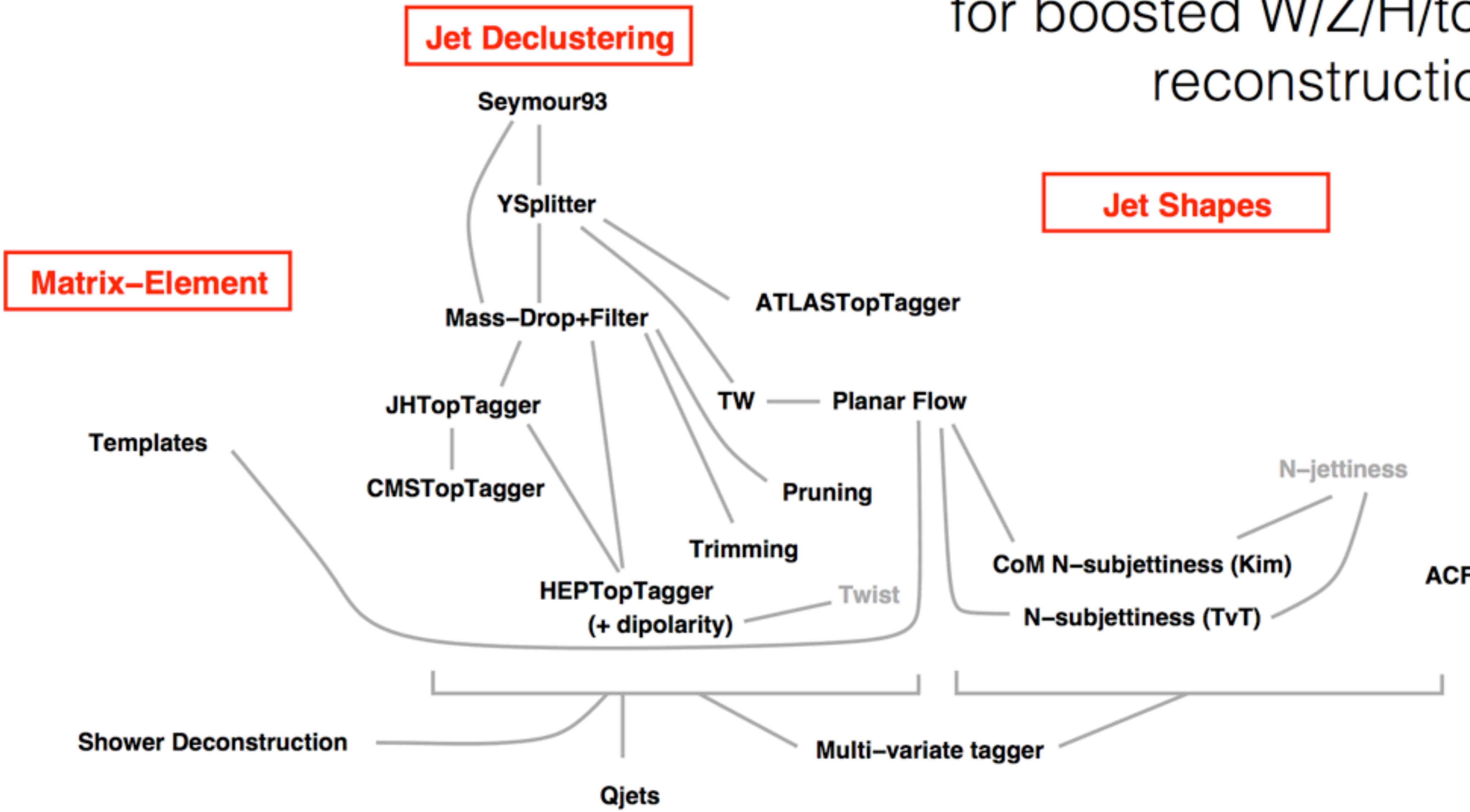
✓ analytical calculations and comparisons to Monte Carlos
✓ study of effect of non-perturbative corrections
✓ performance studies



Example of SoftDrop performance when used as a boosted W tagger

The jet substructure maze

Some of the tools developed for boosted W/Z/H/top reconstruction



Slide by G. Salam, now a few years old

Alternatives to hierarchical substruct.

- If what we are interested in is the structure of the constituents of a jet, the "jet" itself is not the most important feature.
- A different algorithm, or simply the study of the constituents in a certain patch will also do. Selected alternatives are:
  - Use of jet-shapes to characterise certain features
    - e.g. *N-subjettiness*: how many subjets a jets appears to have

      Thaler, van Tilburg, 2011
  - Alternative ways of clustering
    - e.g. *Qjets*: the clustering history not deterministic, but controlled by random probabilities of merging. Can be combined with, e.g. pruning

      Ellis, Hornig, Roy, Krohn, Schwartz, 2012
  - Use information from matrix element
    - e.g. *shower deconstruction*: use analytic shower calculations to estimate probability that a certain configuration comes from signal or from background

      Soper, Spannowsky, 2011
  - Use event shapes mimicking jet properties
    - e.g. *JetsWithoutJets*, mimicking trimming

      Bertolini, Chen, Thaler, 2013

N-subjettiness

Thaler, van Tilburg, 2010

$$\tau_N^{(\beta)} = \sum_i p_{Ti} \min \left\{ R_{1,i}^{\beta}, R_{2,i}^{\beta}, \ldots, R_{N,i}^{\beta} \right\}$$

Sum over constituents of a jet

Distances to axes of N subjets

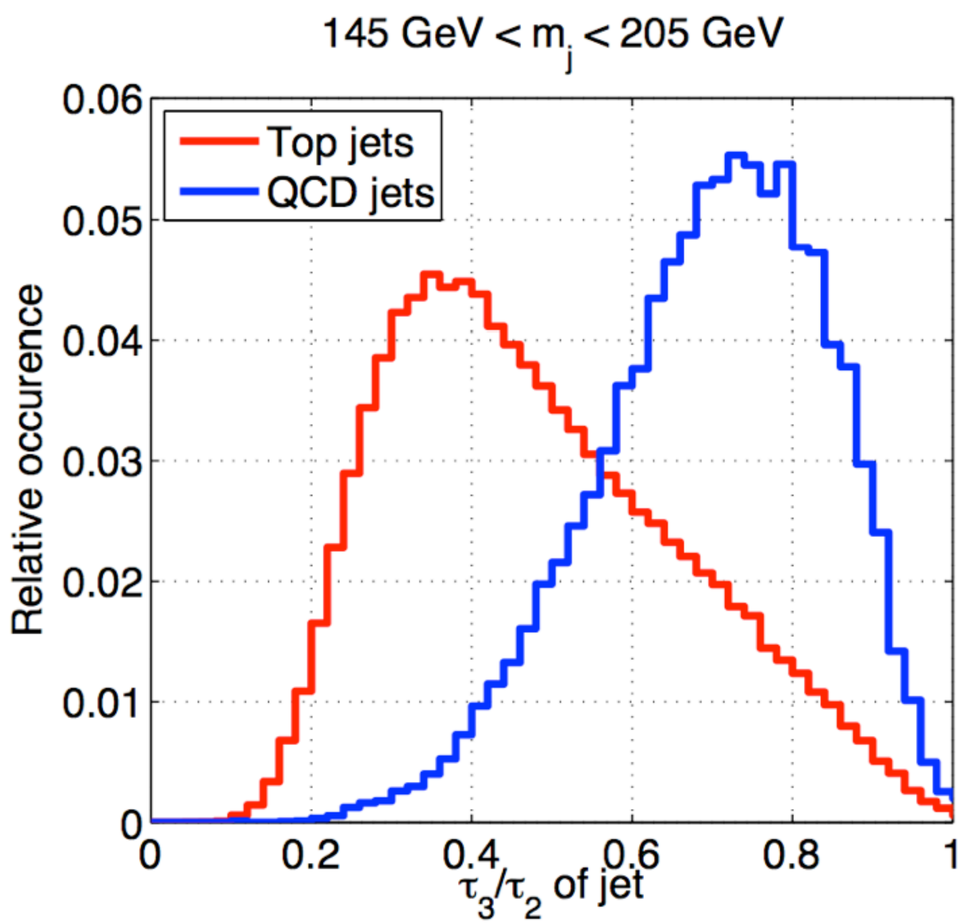
τ_N measures departure from N-parton energy flow:

if a jet has N subjets, τ_{N-1} should be much larger than τ_N

Thaler, van Tilburg, 2010

$$\tau_{N,N-1}^{(\beta)} \equiv \frac{\tau_N^{(\beta)}}{\tau_{N-1}^{(\beta)}}$$

A jet with a **small** $\tau_{N,N-1}$ is more likely to have N than N-1 subjets



(from 1011.2268, with β=1)

C

Larkoski, Salam, Thaler 2013

Energy correlation functions

Probes of N-prong structures without requiring identification of subjets

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\ldots<i_N\in J} \left(\prod_{a=1}^{N} p_{T i_a}\right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} R_{i_b i_c}\right)^{\beta}$$

Angular (y-φ) distances between constituents

ECF(N+1) is zero if there are only N particles

More generally, *if there are N subjets one expects ECF(N+1) to be much smaller than ECF(N)*

[because radiation will be mainly soft/collinear to subjets]

Larkoski, Salam, Thaler 2013

Discriminators

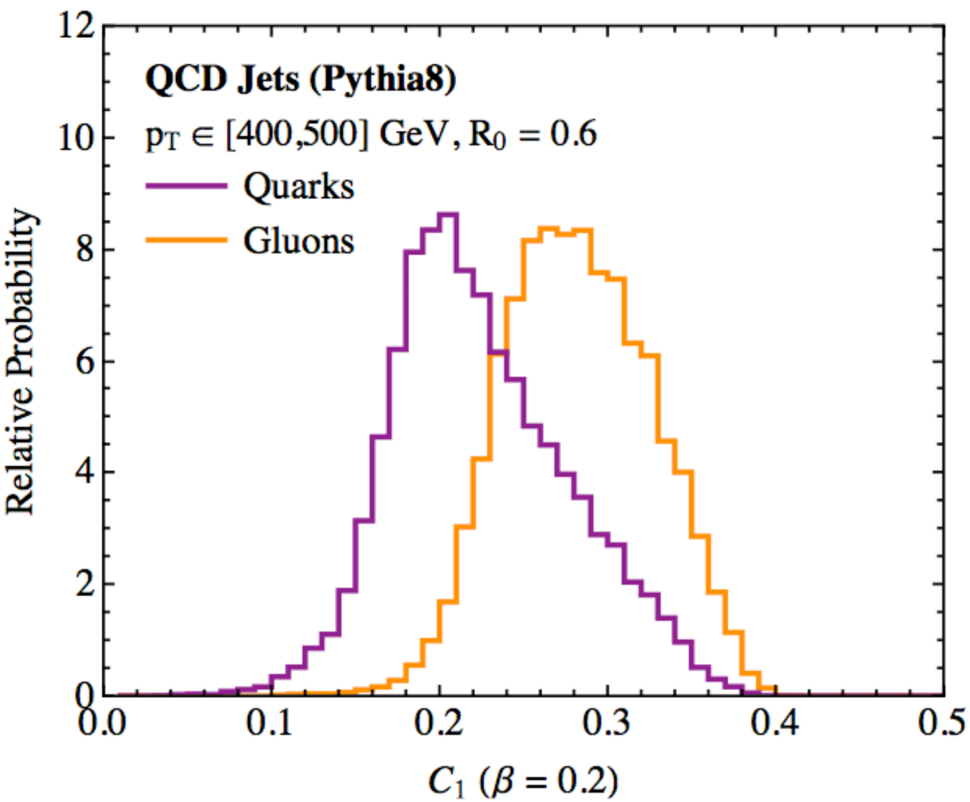
$$r_N^{(\beta)} \equiv \frac{\mathrm{ECF}(N+1,\beta)}{\mathrm{ECF}(N,\beta)}$$

small for N prongs:
if N hard partons, small if radiation
only soft-collinear

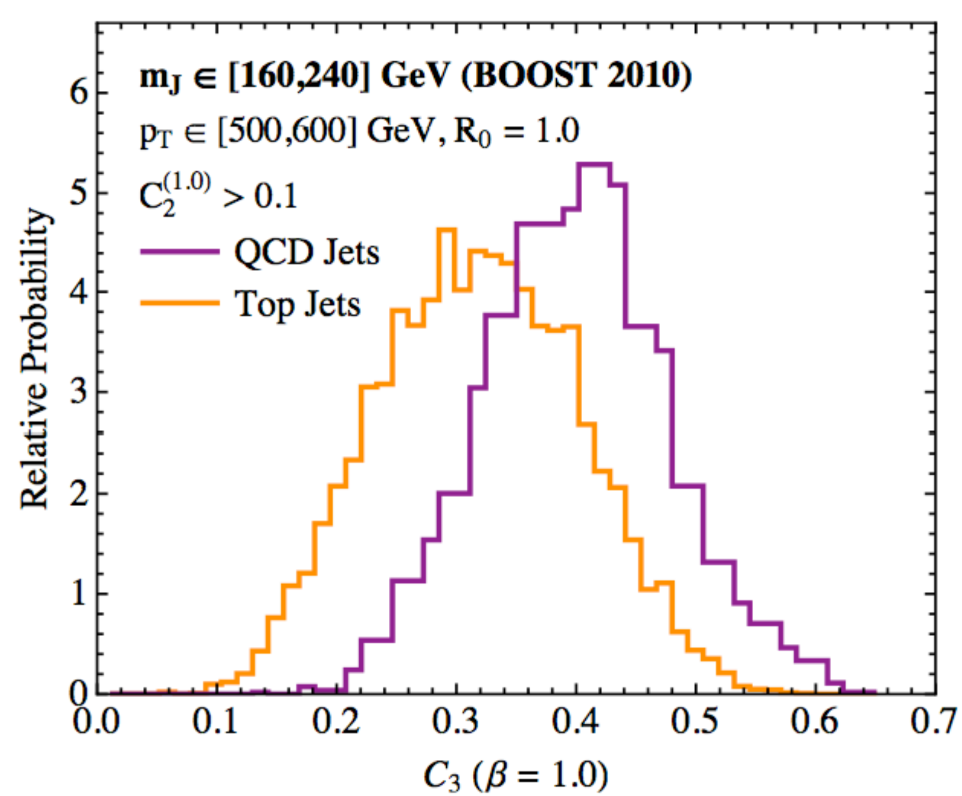
$$C_N^{(\beta)} \equiv \frac{r_N^{(\beta)}}{r_{N-1}^{(\beta)}} = \frac{\mathrm{ECF}(N+1,\beta)\,\mathrm{ECF}(N-1,\beta)}{\mathrm{ECF}(N,\beta)^2}$$

A jet with a **small** C_N is more likely
to have N prongs and at most soft/coll radiation

C₁
quark-gluon discriminator



C₃
top tagging



Note different values of β

(chosen to maximise discriminating power)

Conclusions part I

- A number of different IRC-safe jet algorithms exist
  - They all try to be good proxies for hard partons, but they have different characteristics, especially with respect to soft particles

- Jets from all algorithms inevitably suffer from pileup contamination
  - Techniques exist to subtract it, either at jet-level, or at particle-level

- Both the jet algorithms and many pileup subtraction techniques are packaged either in FastJet or in fjcontrib contributions
  - **Use of standard algorithms and packages** (either directly or through interfaces) **should be privileged**, as it ensures reproducibility

http://fastjet.fr http://fastjet.hepforge.org/contrib/

Conclusions part 2

The big news of the past few years has been the emergence of jet-based taggers and groomers, and more generally of jet substructure studies

- They have proven their worth in ‘Standard Model’ analyses
- They are being implemented in BSM searches
- They are being used in heavy ions physics to probe the details of the parton splittings taking place in quenched jets